THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope

Since the 1968 discovery of huge oil reserves in Prudhoe Bay, Alaska's North Slope has been a site of oil exploration and production that, by the end of 2002, had produced about 14 billion barrels (558 billion gallons) of crude oil. North Slope oil currently averages about 15% of total annual domestic oil production of approximately 3.3 billion barrels and 7% of the annual domestic consumption of approximately 7 billion barrels. Active exploration on the arctic coastal plain is now expanding incrementally westward into the National Petroleum Reserve-Alaska, eastward toward the Arctic National Wildlife Refuge, and south toward the foothills of the Brooks Range (see Figure 1).

Northern Alaska's environment and culture have already been significantly affected by oil infrastructure and activities. There have been many benefits to North Slope residents including more jobs and improved hospitals and schools. These economic benefits have been accompanied by environmental and social consequences, including effects of the roads, infrastructure and activities of oil exploration and production on the terrain, plants, animals and peoples of the North Slope and the adjacent marine environment.

Although a large body of research has assessed actual and potential effects of oil and gas activities and infrastructure, no integrated, comprehensive analysis of *cumulative* effects has previously been attempted. Cumulative effects can result from individually minor but collectively significant actions taking place over a period of time or within an area. In response to a request from Congress, the National Academies convened the Committee on Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope to assess probable cumulative effects of oil and gas activities on various receptors—that is components of the physical, biological, and human systems of the region. The committee's consensus report assesses both present and likely future cumulative effects on the North Slope and adjacent marine waters for the time period of 1965 to 2025 (in some cases to 2050).

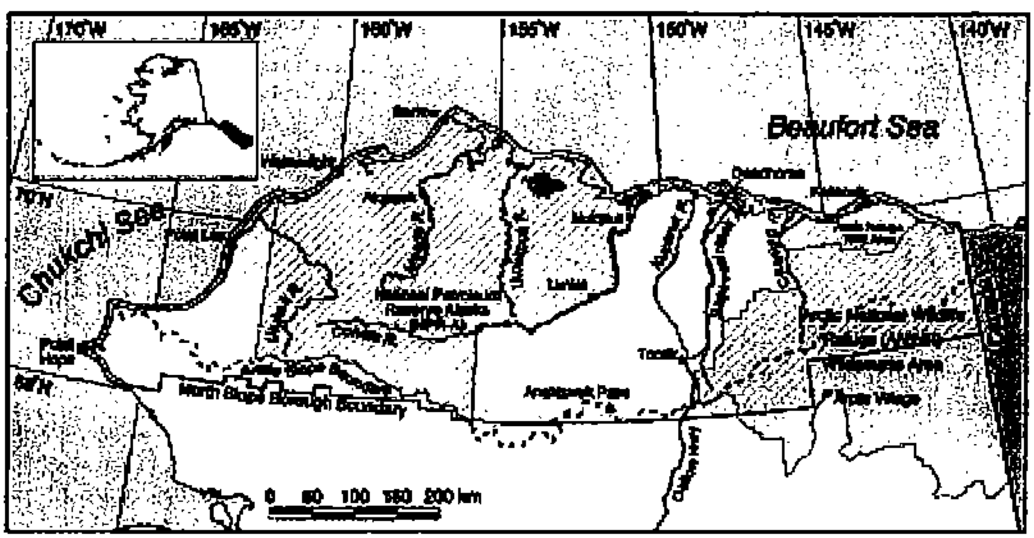


Figure 1. The North Slope (the Arctic Slope) extends from the crest of the Brooks Range to the Arctic Coast, from the Canadian border to Point Hope. Industrial activity has grown from a small operational oil field at Prudhoe Bay to an industrial complex stretching from the Alpine field near the mouth of the Colville River on the west to Badami on the east.

Accumulated Effects To Date

Unlike other U.S. oil fields, those on the North Slope are underlain by permafrost— a thick layer of earth material that stays frozen year round. The permafrost is covered by a thin active layer that thaws each summer and supports plant growth for a brief period. If permafrost thaws, the ground surface and the structures it supports will settle. To minimize disruption to the ground surface, the North Slope industrial infrastructure is specially built—pipelines are generally elevated rather than buried, and roads and industrial facilities are raised on thick gravel berms.

For a variety of reasons, nearly all of the roads, pads, pipelines and other infrastructure ever built are still in place. The environmental effects of such structures on the landscape, water systems, vegetation, and animals are manifest not only at the "footprint" itself (physical area covered by the structure) but also at distances that vary depending on the environmental component being affected. The petroleum industry continues to introduce technological innovations to reduce its footprint, for example, directional drilling and the use of ice roads and pads, drilling platforms, and new kinds of vehicles.

For some areas of concern, the committee found no evidence that effects have accumulated. For example, despite widespread concern regarding the damaging effects of frequent oil and saltwater spills on the tundra, most spills to date have been small and have had only local effects. Moreover, damaged areas have recovered before they have been disturbed again. However, a large oil spill in marine waters would likely have substantial accumulating effects on whales and other receptors because current cleanup methods can remove only a small fraction of spilled oil, especially under conditions of broken ice.

For other areas of concern, effects have accumulated, although in some cases efforts by the petroleum industry and regulatory agencies have reduced them. The committee identified the following areas in which there was evidence of effects that have accumulated.

Roads. Roads have had effects as far-reaching and complex as any physical component of the North Slope oil fields. In addition to their direct effects on the tundra, indirect effects are caused by dust, roadside flooding, thawing of permafrost, and roadside snow accumulation. Roads and activities on them also alter animal habitat and behavior and wildland values and can increase access of hunters, tourists, and others to previously inaccessible parts of the region; enhance communication among communities; and increase contacts between North Slope communities and those outside the area.

Damage to Tundra from Off-Road Travel. Surface erosion, water flow and tundra vegetation on the North Slope have been altered by extensive off-road travel. Some damage has persisted for decades. The current 3-dimensional survey method requires a high density of seismic-exploration trails. Networks of these trails now cover extensive areas and are readily visible from the air, degrading visual experiences of the North Slope. Despite technological improvements and increased care taken by operators, the potential for damage to the tundra still exists because of the large number of vehicles and camps used for exploration.

Effects on Animal Populations. Bowhead whales' fall migrations have been displaced by the noise of seismic exploration. Garbage and food provided by people working in oil fields have resulted in higher than normal densities of predators (such as brown bears, arctic foxes, ravens, and glaucous gulls) that prey on the eggs, nestlings, and fledglings of birds. As a result, the reproduction rates of some bird species such as black brant, snow geese, eiders, and probably some shorebirds in industrial areas are, at least in some years, insufficient to balance death rates. These populations may persist in the oil fields only because of immigration of individuals from source areas where birth rates exceed death rates.

The combined effects of industrial activity and infrastructure and the stress imposed by insects in some summers reduced calf production in the Central Arctic caribou herd and may have contributed to the reduction in herd size from 1992 through 1995. In contrast, the herd increased in size from 1995 to 2001, when insect activity was lower. Although accumulated effects have not prevented an increase in the overall size of the Central Arctic Herd, the spread of industrial activity into other areas caribou use for calving and insect relief, especially to the east where the coastal plain is narrower, would likely affect reproductive success, unless the degree to which it disturbs caribou can be reduced.

Interactions of Climate Change and Oil Development. Global and regional climates have changed throughout the Earth's history, but climate changes during the past several decades on the North Slope have been unusually rapid. If recent warming trends in climate continue, as many projections indicate, the effects will accumulate over the next century to alter the extent and timing of sea ice, affect the distribution and abundance of marine and terrestrial plants and animals, and affect permafrost as well as the usefulness of current oil-field technologies and how they affect the environment.

Interference with Subsistence Activities. The Inupiat Eskimo people of the North Slope have a centuries-old nutritional and cultural relationship with the bowhead whale. Most view offshore industrial activity—both observed effects and the possibility of a major oil spill—as a threat to the bowhead whale and, thereby, to their cultural survival. Because noise from exploratory drilling and marine seismic exploration have caused fall migrating bowhead whales to change their movements, subsistence hunters have been forced to travel greater distances to find whales, increasing their risk of exposure to adverse weather and the likelihood that a whale's tissues will have deteriorated before the carcass can be landed. Recent agreements concerning the timing and placement of exploration in the fall have reduced the effects on subsistence hunters.

The Gwich'in Indians of northeast Alaska and northwest Canada have a centuries-old nutritional and cultural relationship with the Porcupine Caribou Herd. Most Gwich'in oppose any oil development that would threaten the herd, especially on the calving ground, which they consider sacred, and thereby threaten their cultural survival. These threats have accumulated because repeated attempts to develop areas used by the herd have occurred and will probably continue to occur.

Social Changes in North Slope Communities. Most North Slope residents have positive views of many of the economic changes that have resulted from revenue generated by petroleum activities, such as access to better medical care, availability of gas heat for houses, improved plumbing, and higher personal incomes. At the same time, however, balancing the economic benefits of oil activities against the accompanying loss of traditional culture and other societal problems that can occur is often a dilemma for North Slope residents. Without this revenue, the North Slope Borough, the Alaska Native Claims Settlement Act, and hence the Arctic Slope Regional Corporation, would not exist or, if they did, would bear little resemblance to their current form. This discovery of oil and its development on the North Slope has resulted in major, important, and probably irreversible changes to the way of life in communities. These effects accumulate because they arise from several ongoing, interacting causes.

Cumulative Aesthetic, Cultural, and Spiritual Consequences. Many activities associated with oil development have compromised wildland and scenic values over large areas. Some Alaska Natives told the committee that they violate what they call "the spirit of the land," a value central to their relationship with the environment. These consequences have increased in proportion to the area affected by development, and they will persist as long as the landscape remains altered.

Future Accumulation of Effects

The committee assessed possible future accumulation of effects, assuming conditions favorable to continued expansion of oil and gas activities using technology and regulatory oversight at least as good as those currently used.

Response of North Slope Cultures to Declining Revenues. For North Slope residents, the current way of life of North Slope communities made possible by oil and gas activities will be more difficult to maintain when these activities cease as oil is depleted because other sources of funds appear to be modest. Eventual adjustments to reduced financial resources are unavoidable. Their nature and extent will be shaped by adaptations North Slope communities have made to the accumulated effects of the cash economy.

Legacy of Abandoned Infrastructure and Unrestored Landscapes. The network of roads, pads and pipelines, and infrastructure that support production will likely remain in place for many years to come. The oil industry and regulatory agencies have made dramatic progress in reducing the effects of new gravel fill by reducing the size of the gravel footprint required for many types of facilities and substituting ice for gravel for certain types of roads and pads. However, much less attention has been directed to restoring already disturbed sites. To date, only about 1% of the habitat on the North Slope affected by gravel fill has been rehabilitated.

With the exception of well-plugging and abandonment procedures, state, federal, and local agencies have largely deferred decisions regarding the nature and extent of restoration that will be required. Because the obligation to restore sites is unclear, and the costs of dismantlement, removal, and restoration are likely to be very high, the committee judges it unlikely that most disturbed habitats on the North Slope will be restored. Because natural recovery in the Arctic is slow, the effects caused by abandoned and unrestored infrastructure are likely to persist for centuries and could accumulate further as new structures are added.

Expansion of Activities into New Areas. Expansion of oil and gas exploration is spreading into hillier terrain and into coastal plain areas with soils, vegetation and aquatic environments that differ substantially from current areas of activity. To assess effects in these environments, they should be characterized through description of topography, permafrost conditions, sand, gravel, and water availability, hydrological conditions, and a description of the biotic communities present. In addition, future exploratory activity will probably be carried out in a warming climate, with milder winter temperatures and shorter periods of freezing conditions.

Filling Knowledge Gaps

As industrial activities proceed, it is vital to continue collecting and analyzing information on the North Slope's physical, biological, and human environments to help decision makers in developing and implementing effective natural resources management. Advantage should be taken of opportunities to learn from these activities (adaptive management).

Decisions about where, when, and under what conditions and requirements industrial activities are permitted on the North Slope are made by many different federal, state, regional, and municipal government agencies. To date, decisions have generally been made without a comprehensive slope-wide plan and regulatory strategy that identify the scope, intensity, direction and consequences of industrial activities judged acceptable. A comprehensive framework and plan should be developed for the North Slope so that actions can be evaluated with respect to their compatibility with overall goals, the likely effects of individual activities on all receptors that might be affected by them, and the likelihood that the activities will result in long-term or difficult-to-reverse undesirable effects. Knowledge gaps should be addressed through the following:

- Ecosystem-level research in addition to local ecological studies.
- Studies to understand the types of effects that exist at varying distances beyond the footprint of industrial structures.
- Studies of air pollution that provide a quantitative baseline of spatial and temporal trends in air quality over long periods across the North Slope.
- Studies of effects of seismic exploration and other off-road use on the tundra.
- Research on habitat requirements of caribou, their reproductive physiology and movements, and how natural and anthropogenic disturbance affects them.
- Studies of the effects of noise on the migratory and acoustic behavior of bowhead whales and on their feeding habits in the Alaskan portion of the Beaufort Sea.
- Studies of effects of taking water from lakes on the North Slope for ice roads, pads, and other purposes.
- Studies of methods to reduce effects of oil spills including non-mechanical methods of cleaning up oil spilled in the sea, especially in broken ice.
- Research on the specific benefits and threats that North Slope residents perceive.
- Studies of effects of oil and gas activities on human health including studies of increased use of alcohol and drugs, increased obesity, and other societal ills.

This summary was prepared by the National Research Council based on the committee's report. For more information: Contact the National Research Council's Board on Environmental Studies and Toxicology at 202-334-3060. *Cumulative Environmental Environmental Effects of Oil and Gas on the North Slope* is available from the National Academies Press, Fifth Street, NW, Washington, DC 20001; 800-624-6242 or 202-334-3313 (in the Washington area); http://www.nap.edu.

Committee on Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope: Gordon Orians, (Chair), University of Washington; **Thomas Albert,** North Slope Borough; **Gardner Brown,** University of Washington; **Raymond Cameron,** University of Alaska; **Patricia Cochran,** Alaska Native Science Commission; **S. Craig Gerlach,** University of Alaska; **Robert Gramling,** University of Louisiana; **George Gryc,** U.S. Geological Survey; **David Hite,** Geological Consultant, Anchorage; **Mahlon Kennicutt II,** Texas A&M University; **Arthur Lachenbruch,** U.S. Geological Survey; **Lloyd Lowry,** University of Alaska; **Lawrence Moulton,** MJM Research; **Chris Pielou,** Dalhousie University; **James Sedinger,** University of Nevada; **K. June Lindstedt-Siva,** ENSR Consulting and Engineering; **Lisa Speer,** Natural Resources Defense Council; **Donald (Skip) Walker,** University of Alaska; **David Policansky** (Project Director), Board on Environmental Studies and Toxicology.

PREPUBLICATION COPY

Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope

Committee on the Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope

Board on Environmental Studies and Toxicology

Polar Research Board

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

March 2003

THE NATIONAL ACADEMIES PRESS **500 Fifth Street, N.W.** **Washington, D.C. 20001**

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This project was supported by Contract No. X-82827701 between the National Academy of Sciences and the U.S. Environmental Protection Agency. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the organizations or agencies that provided support for this project.

Library of Congress Control Number

International Standard Book Number

Additional copies of this report are available from:

The National Academies Press
500 Fifth Street, NW
Box 285
Washington, DC 20055

800-624-6242
202-334-3313 (in the Washington metropolitan area)
http://www.nap.edu

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Wm. A. Wulf is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. Wm. A. Wulf are chair and vice chair, respectively, of the National Research Council

www.national-academies.org

COMMITTEE ON CUMULATIVE ENVIRONMENTAL EFFECTS OF OIL AND GAS ACTIVITIES ON ALASKA'S NORTH SLOPE

GORDON ORIANS, (*Chair*), University of Washington (retired), Seattle, Washington
THOMAS ALBERT, North Slope Borough (retired), Laurel, Maryland
GARDNER BROWN, University of Washington (retired), Seattle, Washington
RAYMOND CAMERON, University of Alaska (retired), Fairbanks, Alaska
PATRICIA COCHRAN, Alaska Native Science Commission, Anchorage, Alaska
S. CRAIG GERLACH, University of Alaska, Fairbanks, Alaska
ROBERT GRAMLING, University of Louisiana, Lafayette, Louisiana
GEORGE GRYC, U.S. Geological Survey (Emeritus), Menlo Park, California
DAVID HITE, Geological Consultant, Anchorage, Alaska
MAHLON KENNICUTT II, Texas A&M University, College Station, Texas
ARTHUR LACHENBRUCH, U.S. Geological Survey (Emeritus), Menlo Park, California
LLOYD LOWRY, University of Alaska (retired), Fairbanks, Alaska
LAWRENCE MOULTON, MJM Research, Lopez Island, Washington
CHRIS PIELOU, Dalhousie University (retired), Comox, British Columbia, Canada
JAMES SEDINGER, University of Nevada, Reno, Nevada
K. JUNE LINDSTEDT-SIVA, ENSR Consulting and Engineering, Banning, California
LISA SPEER, Natural Resources Defense Council, New York, New York
DONALD (SKIP) WALKER, University of Alaska, Fairbanks, Alaska

Staff

DAVID POLICANSKY, Project Director
CHRIS ELFRING, Polar Research Board Director
SUZANNE VAN DRUNICK, Staff Officer
MEG WALSH, Postdoctoral Research Associate
MIRSADA KARALIC-LONCAREVIC, Research Assistant
KATE KELLY, Editor
LEAH PROBST, Senior Program Assistant
JESSICA BROCK, Senior Project Assistant
DOMINIC BROSE, Project Assistant

BOARD ON ENVIRONMENTAL STUDIES AND TOXICOLOGY

Members

GORDON ORIANS *(Chair)*, University of Washington, Seattle, Washington
JOHN DOULL *(Vice Chair)*, University of Kansas Medical Center, Kansas City, Kansas
DAVID ALLEN, University of Texas, Austin, Texas
THOMAS BURKE, Johns Hopkins University, Baltimore, Maryland
JUDITH CHOW, Desert Research Institute, Reno, Nevada
CHRISTOPHER B. FIELD, Carnegie Institute of Washington, Stanford, California
WILLIAM GLAZE, University of North Carolina, Chapel Hill, North Carolina
SHERRI GOODMAN, Center for Naval Analyses Corporation, Alexandria, Virginia
DANIEL S. GREENBAUM, Health Effects Institute, Cambridge, Massachusetts
ROGENE HENDERSON, Lovelace Respiratory Research Institute, Albuquerque, New Mexico
CAROL HENRY, American Chemistry Council, Arlington, Virginia
ROBERT HUGGETT, Michigan State University, East Lansing, Michigan
BARRY L. JOHNSON, Emory University, Atlanta, Georgia
JAMES H. JOHNSON, Howard University, Washington, D.C.
JAMES A. MACMAHON, Utah State University, Logan, Utah
PATRICK V. O'BRIEN, Chevron Research and Technology, Richmond, California
DOROTHY PATTON, Washington, D.C.
ANN POWERS, Pace University School of Law, White Plains, New York
LOUISE M. RYAN, Harvard University, Boston, Massachusetts
JONATHAN SAMET, Johns Hopkins University, Baltimore, Maryland
KIRK SMITH, University of California, Berkeley, California
LISA SPEER, Natural Resources Defense Council, New York, New York
G. DAVID TILMAN, University of Minnesota, St. Paul, Minnesota
CHRIS G. WHIPPLE, Environ, Inc., Emeryville, California
LAUREN ZEISE, California Environmental Protection Agency, Oakland, California

Senior Staff

JAMES J. REISA, Director
DAVID J. POLICANSKY, Associate Director and Senior Program Director for Applied Ecology
RAYMOND A. WASSEL, Senior Program Director for Environmental Sciences and Engineering
KULBIR BAKSHI, Program Director for the Committee on Toxicology
ROBERTA M. WEDGE, Program Director for Risk Analysis
K. JOHN HOLMES, Senior Staff Officer
SUSAN N. J. MARTEL, Senior Staff Officer
SUZANNE VAN DRUNICK, Senior Staff Officer
EILEEN N. ABT, Senior Staff Officer
ELLEN K. MANTUS, Senior Staff Officer
RUTH E. CROSSGROVE, Managing Editor

POLAR RESEARCH BOARD

Members

ROBIN BELL *(Chair)*, Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York
RICHARD ALLEY, Pennsylvania State University, University Park, Pennsylvania
AKHIL DATTA-GUPTA, Texas A&M University, College Station, Texas
GEORGE DENTON, University of Maine, Orono, Maine
HENRY P. HUNTINGTON, Huntington Consulting, Eagle River, Alaska
AMANDA LYNCH, University of Colorado, Boulder, Colorado
ROBIE MACDONALD, Fisheries and Oceans Canada, Sidney, British Columbia, Canada
MILES MCPHEE, McPhee Research Company, Naches, Washington
CAROLE L. SEYFRIT, Old Dominion University, Norfolk, Virginia

Staff

CHRIS ELFRING, Director
ANN CARLISLE, Senior Project Assistant

Preface

Since production began on Alaska's North Slope in the early 1970s, about 14 billion barrels of oil have been extracted from underground deposits and sent to markets elsewhere. As much as 20 billion additional barrels of oil might be extracted from the area. In addition, the region has huge reserves of natural gas and coal. Therefore, if market conditions remain favorable, exploration and extraction are likely to continue on the North Slope and to expand into areas that have until now been uninfluenced by industrial activity.

The residents of Alaska and throughout the United States have benefited from oil and gas production on the North Slope, but, as with all industrial developments, these activities have brought with them social and environmental costs. Although research has been carried out on the North Slope during the past several decades to understand the effects of oil and gas exploration, development, and production, an integrated, comprehensive assessment of those effects has not been attempted. Understanding the nature, extent, and causes of both the benefits and costs is an essential component of effective, long-term decision-making about resource management on the North Slope.

To rectify this gap in knowledge, the United States Congress asked the National Research Council to review information about oil and gas activities on Alaska's North Slope and to assess their known and probable future cumulative effects on the physical, biological, and human environment. The NRC established a committee whose 18 members had expertise in a wide range of disciplines, including geology, hydrology, physics of permafrost, biology, sociology, anthropology, and economics. In making its assessments, the committee relied on its collective expertise, extensive literature review, information gathered during public meetings held in various places in Alaska, and written materials supplied by many individuals and organizations.

The task undertaken by the committee was difficult. The area of concern—from the crest of the Brooks Range to the Arctic Ocean and from the Canadian border on the east to the Chukchi Sea on the west—is about the size of Minnesota. It includes the continental shelf and coastal waters, flat coastal tundra, undulating foothills, rivers, lakes, and mountain slopes. Industrial activity has affected primarily the area between the Canning River and the eastern part of the National Petroleum Reserve-Alaska, but more of the North Slope could be influenced by future developments. During the several decades over which industrial activities expanded on the North Slope, technological advances dramatically changed how the industry operated and how it influenced the North Slope environment. There is every reason to believe that technical innovations will continue in the future, adding to the difficulty of making projections of future cumulative effects. In addition, the climate of the North Slope has warmed considerably during the past several decades, and the rate of warming is likely to accelerate in the future. Climate change is likely to influence nearly all aspects of industrial activity in the area and the effect of those activities on the environment.

Because of the complexity of its task, the committee met eight times. Members visited the North Slope during both winter and summer conditions. Its sessions sometimes lasted as long as a week, during which there were extensive in-depth discussions of the available data and their interpretation. Considerable work was carried out between meetings by both committee members and NRC staff. Despite the highly varied professional backgrounds, knowledge, and perceptions of the committee members, candor, mutual respect, and collegiality dominated the committee's proceedings. This spirit of cooperation made this consensus report possible.

The committee was ably assisted by staff of the Board on Environmental Studies and Toxicology (BEST) and the Polar Research Board (PRB), the two NRC boards under whose auspices the study was carried out. The efforts and experience of David Policansky (BEST) and Chris Elfring (PRB) assisted the committee in numerous ways and helped keep us on track. James Reisa (BEST) provided his usual thoughtful advice. Logistical, informational, and other invaluable support was provided by BEST staff members, especially Leah Probst, Jessica Brock, Dominic Brose, Margaret Walsh, and Suzanne van Drunick. Walter Gove provided much useful information to the committee, as did the many people who made presentations to the committee and helped us on our visits (please see Appendix B for list of participants in our meetings).

Many people made our task possible by providing information, hospitality, and logistic support. We thank the governments and people of Arctic Village, Barrow, Kaktovik, and Nuiqsut for their kindness, as well as members of the North Slope Borough. We thank representatives of the oil industry for sharing information and logistic support, in particular Joseph Hegna of Phillips Petroleum and Bill Streever and Steve Taylor of BP. Theodore (Ted) Rockwell, Lisa Morales, and Tracy Nadeau of EPA provided advice, encouragement, and information to the committee while serving as the sponsoring agency's technical representatives. We also thank the other state and federal agencies and members of the public who provided us with information, guidance, and assistance.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Garry D. Brewer, Yale University
Ingrid C. Burke, Colorado State University
Brian Davies, BP Exploration-Alaska (retired)
William L. Fisher, University of Texas
Richard Glenn, Arctic Slope Regional Corporation
Mike Joyce, ARCO Alaska (retired)
John McDonagh, Alaska Office of the Oil and Gas Coordinator (retired)
Edna McLean, Ilisagvik College
Pamela A. Miller, Arctic Connections
Don Russell, Canadian Wildlife Service, Environment Canada

Stan Senner, Alaska Audubon
John J. Stegeman, Woods Hole Oceanographic Institution
Arlon R. Tussing, Institute of the North
Gunter Weller, University of Alaska Fairbanks
William J. Wilson, LGL Alaska Research Associates, Inc.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by John Bailar, University of Chicago (emeritus) (review monitor) and Wilford Gardner, University of California, Berkeley (emeritus) (review coordinator). Appointed by the NRC, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Important though it is to identify and assess the nature of cumulative effects and their causes, the committee recognizes that this knowledge, by itself, cannot specify public policy. Nonetheless, without such analyses, decision-makers lack a background against which to evaluate the assertions of different groups that have specific benefits to gain from policies or who are likely to bear the brunt of costs. The committee has identified the most important cumulative effects of oil and gas development on the North Slope and has attempted to show why they have happened. The committee has also concluded that some effects have been much less important than they are widely believed to be. Therefore, this report should help focus future discussions on the major cumulative effects of industrial development on the North Slope. It should also direct attention to the inevitable tradeoffs that must be balanced when choosing future management options and the rules and regulations under which they will be carried out. If this report serves that purpose, we will all consider ourselves suitably rewarded for our efforts.

Gordon H. Orians
Chair, Committee on Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope

Contents

Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope

Summary

Oil fields on land and off the coast of Alaska's North Slope, including the Prudhoe Bay field, have produced about 14 billion barrels (bbl) of crude oil through the end of 2002 (one barrel equals 42 U.S. gal or 159 L). North Slope oil has averaged about 20% of U.S. domestic production since 1977, and it currently provides about 15% of the annual domestic production of approximately 3.3 billion bbl and 7% of the annual domestic consumption of approximately 7 billion bbl. If production of the large reserves of natural gas in the region were to become economically feasible, the strategic and economic importance of the North Slope's hydrocarbon energy resources would be even greater.

Oil and gas production on the North Slope has brought positive and negative consequences—economic, social, and environmental. Environmental consequences of concern include the effects of oil-related structures and activities on the migration of fish and marine and terrestrial mammals, especially bowhead whales and caribou. Concerns have also been raised about the risk of toxic contamination of plants and animals used for food by Alaska Natives, effects of oil and gas exploration and development on tundra and marine ecosystems, and effects of oil spills on marine and coastal ecosystems. Also of concern are the effects of oil activities and structures on endangered or threatened species, migratory birds, polar bears and other mammals, and on wildland (wilderness) values. Some of the socioeconomic changes resulting from oil and gas development, including those involving employment, lifestyles, health, and other aspects of people's lives, also have been of concern.

Considerable research has been done on various actual and potential effects of oil and gas activity on the North Slope's physical, biotic, and human environments. Reviews of this research have appeared in environmental impact statements (EISs), in reports funded by the Department of the Interior and other federal and state agencies, in oil industry publications, in journals, and in National Research Council reports, among others. However, there has been little assessment of the *cumulative* effects of those activities, the elucidation of which is critical to support informed, long-term decision-making about resource management. To address this lack of information and understanding, the Congress requested that the National Academies review and assess what is known about the cumulative environmental effects of oil and gas activities on Alaska's North Slope.

THE PRESENT STUDY

In response to the request from Congress, the National Academies established the Committee on Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North

Slope, which prepared this report. The committee was directed to review information about oil and gas activities (including cleanup efforts) on the North Slope and, based on its review, to assess the known and probable cumulative impacts of such activities on the physical, biotic, and human environments of the region and its adjacent marine environment. The committee also was directed to assess likely future cumulative effects, based on its judgment of probable changes in technology and the environment, under a variety of scenarios for oil and gas production, and in combination with other probable human activities, including tourism, fishing, and mining. Although the cumulative effects of North Slope oil and gas activities—especially production—extend beyond the region, the committee's focus was confined to Alaska's North Slope and as far into the Arctic Ocean as there is evidence of environmental effects.

The committee met eight times over the course of its two-year study. In Alaska, it met in Anchorage, Fairbanks, Barrow, Nuiqsut, Arctic Village, and Kaktovik. It heard from federal and state agencies, representatives of the oil and gas industry, environmental organizations, and officials and community members of the North Slope Borough and the municipalities it visited. It toured the oil facilities at Prudhoe Bay, Endicott, and Alpine, and flew over the Arctic National Wildlife Refuge, the National Petroleum Reserve-Alaska, Kuparuk, and the Northstar production facility. It also held meetings in executive session to write the report. Appendix A lists those who participated in the meetings.

UNDERSTANDING AND ASSESSING CUMULATIVE ENVIRONMENTAL EFFECTS

The basic issue of cumulative-effects assessment is that when numerous small decisions about related environmental matters are made independently, the combined consequences of those decisions are often not considered. The result is that patterns of the environmental perturbations or their effects over large areas and long periods are not analyzed.

The committee has followed the generally accepted approach to identifying and assessing cumulative effects that evolved after passage of the National Environmental Policy Act (NEPA) of 1969. The NEPA requires federal agencies to develop EISs for many major projects. If a project—and its EIS—is considered in isolation from similar projects or separately from diverse projects in the same area, some cumulative effects are likely to be missed. In 1978, the Council on Environmental Quality promulgated regulations to implement the NEPA that are binding on all federal agencies. A cumulative effect was defined as "...the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions....Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time." The practice of cumulative-effects assessment arose to address such problems.

In interpreting the broad charge of assessing cumulative effects, the committee focused on whether the effects under consideration interact or accumulate over time and space, either through repetition or in combination with other effects, and under what circumstances and to what degree they might accumulate. As an example, consider a repeated environmental insult that is localized in space and occurs so infrequently that natural processes of recovery or human efforts can eliminate its effects before another insult occurs. In this case, one would conclude that the effects of the insult do not accumulate (rather than concluding that the insult is not "a cumulative effect"). This approach also directs attention to the circumstances under which effects might accumulate.

Although the assessment of cumulative effects has a history of several decades, doing it well remains challenging and complex, because a full analysis of how and when such effects accumulate requires the synthesis of multiple individual assessments. To address this problem, the committee developed a general process to identify how effects accumulate with respect to different receptors, i.e., the organisms, communities, and environments that are affected. The key elements are: (a) specify the class of actions whose effects are to be analyzed; (b) designate the time and space scales over which the relevant actions take place; (c) identify and characterize the receptors whose responses to the actions are to be assessed; and (d) determine the magnitude of the effects on the different receptors and whether they are accumulating or interacting with other effects.

At the most general level, the class of actions considered by the committee consisted of all activities associated with oil and gas development. The spatial area was the Alaska Arctic Slope and adjacent marine waters. The temporal period was 1965 to 2025, and the receptors were the physical, biological, and human systems of the region.

Effects typically accumulate as the result of repeated activities of similar or different types. However, in some cases the effects of a single action or event can accumulate. This is especially true if the effects persist for a long time and are augmented by the effects of other activities.

Beyond simply identifying the accumulation of effects, their magnitude and their biotic and socioeconomic importance must be assessed. The committee assessed biotic and socioeconomic importance separately for each receptor. The importance of effects is perceived differently by different individuals or groups. The committee is not aware of a satisfactory way of attributing some absolute degree of importance to effects, and so it attempted to describe the basis on which it assessed the importance of the effects. For example, in assessing importance, the committee considered factors such as ecological consequences, importance attributed by North Slope residents, economic consequences for North Slope residents, irreversibility, and degree of controversy.

OVERVIEW OF THE NORTH SLOPE ENVIRONMENT

Climate

The North Slope—or Arctic Slope—of Alaska is the 230,000 km^2 (89,000 mi^2) region north of the crest of the Brooks Range, an area slightly larger than Minnesota (Figure S-1). It encompasses the drainage basins that empty into the Beaufort and Chukchi Sea. The land slopes gradually from the crest of the rugged Brooks Range northward to the Arctic Ocean. Summer temperatures on the coastal plain are usually between 5 and 15 °C (40-60 °F); they can be higher for short periods, especially inland. Winter temperatures are usually below minus 18 °C (0 °F) and sometimes below minus 40 °C (minus 40 °F). From November 18 to January 24, the sun never rises above the horizon at Barrow, but there is a little midday twilight. The sun does not set from May 10 until August 2. Annual precipitation ranges from 12 to 20 cm (5-8 in.) in coastal and foothill areas and up to 100 cm (40 in.) in the highest elevations of the Brooks Range. Extensive areas are covered by thaw lakes, ice-wedge polygons, frost boils, water tracks, bogs, and other features typical of permafrost regions. Snowfall is difficult to measure accurately, but

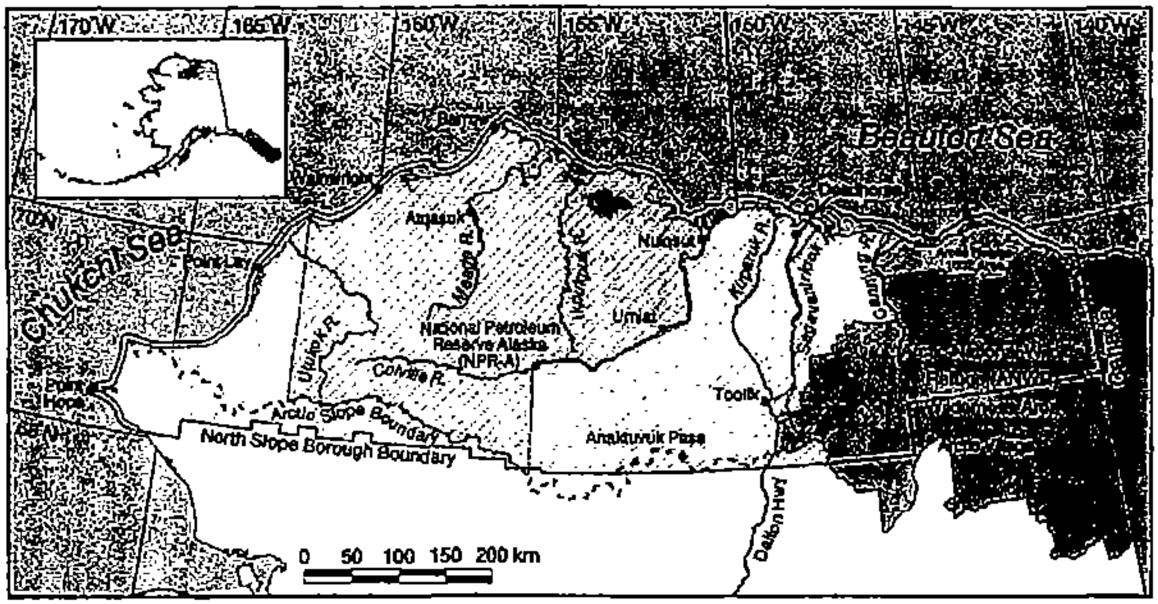


FIGURE S-1. The Alaska North Slope region. The dashed line is the southern boundary of the drainage basin. The Trans-Alaska Pipeline is close to the Dalton Highway. Source: Alaska Geobotany Center, University of Alaska Fairbanks 2002.

probably averages less than 50 cm (20 in.) in most coastal areas and more than 2 m (80 in.) in some mountain areas.

Permafrost

Alaska's North Slope is underlain by permafrost, earth material whose temperature stays below freezing year-round. Along the Arctic coast, the permafrost extends to depths of 200-650 m (650-2,100 ft), the deepest occurring near Prudhoe Bay. Permafrost is important primarily because its groundwater generally occurs as ice, often in massive forms. If the ice melts, the ground surface can become unstable and can subside substantially. Thus permafrost poses special problems for the development of industrial infrastructure and the preservation of natural systems.

Permafrost is separated from the ground surface by an active layer that thaws each summer to depths ranging from 20 cm (8 in.) to more than 2 m. The active layer sustains tundra plants, which in turn sustain animals and control processes of surface erosion and water flow.

Changes in surface conditions, such as disruption of the insulating organic mat or impoundment of surface water, can cause the surface to settle and create thermokarst—a disruption of the tundra's surface associated with warming and thawing of permafrost. This process is difficult to reverse and has ecological effects as well as effects on structures. To maintain permafrost, activities on the tundra must be controlled carefully, and buildings, roads, and other structures must be designed to avoid thawing their own foundations. Special conditions exist offshore where development takes place on deep permafrost warmed by the sea to temperatures close to melting. Engineering designs for the infrastructure might eventually have to be reconsidered if North Slope climates warm as predicted in the twenty-first century.

Geomorphology

The North Slope is divided into three major regions: the arctic coastal plain, the arctic foothills, and the Brooks Range. To date, all oil production has occurred on the coastal plain, but there is increasing exploration in the foothills. The only directly influenced area in the Brooks Range is the corridor for the Trans-Alaska Pipeline, which crosses those mountains at Atigun Pass.

Surface Water

The Arctic coastal plain is generally flat, with large thaw lakes (formed when the tundra surface thaws in summer) and extensive wetlands that are important habitat for waterfowl and shorebirds. Lakes and ponds are among its most striking landforms. Most lakes in the developed oil-field region between the Sagavanirktok and Colville rivers are shallow, typically less than 6 ft (1.8 m) deep. Lakes are deeper to the west and south, with mean maximum depths of more than 30 ft (9 m) in lakes south of Teshekpuk Lake, the largest lake on the coastal plain (816 km^2 or 315 mi^2). Lakes on the coastal plain are typically ice-covered from early to mid-October until early July. During winter, flow ceases in the region's many rivers, and ice develops to a thickness of about 1.8 m (6 ft). Spring break-up begins in the Brooks Range and foothills, which warm more rapidly than does the coastal plain. During this time, the lower reaches of rivers are frozen, and the tundra is still snow-covered. Thus, there is substantial ice-jamming and over-bank flooding.

Terrestrial Biota

The Arctic Coastal Plain has the largest expanse of arctic fens (mineral-rich, sedge-covered wetlands) and thaw lakes in the world, and the foothills comprise the largest expanse of tussock tundra (tundra dominated by the cottongrass *Eriophorum vaginatum*) in the world.

The most important consumers of living and dead plant tissues in terrestrial arctic tundra are mammals, birds, arthropods, and nematodes. The mammals include caribou, moose, muskoxen, grizzly bears, foxes, and wolves. Most bird species that breed in Alaska north of the Brooks Range nest in tundra habitats, associated wetlands, or adjacent marine lagoons. The dominant groups, both in the number of species and in their abundance, are waterfowl—ducks, geese, and swans—and shorebirds. Loons and some other species are of concern because their populations are generally declining elsewhere in and outside Alaska.

No cold-blooded terrestrial vertebrates can survive the arctic cold; birds and mammals are the only terrestrial vertebrates. The most abundant and important terrestrial invertebrates are insects. In fresh water, most fish species spend their lives in rivers and lakes, although some migrate between fresh water and coastal marine waters.

Marine Ecology

The nearshore marine environment contains three main aquatic habitats: delta fronts (places where fresh water from river deltas meets coastal marine water), coastal lagoons, and open coast. Some areas of the coast are open and directly exposed to the wind, wave, and current action of the Arctic Ocean. Other stretches of the shore are protected by chains of barrier islands.

The sea is usually covered in ice from November through June. High rates of primary productivity are normally associated with the ice edge and areas of upwelling.

The Arctic Ocean supports a specialized biotic community, despite its low biological productivity. However, especially near the coast, there is relatively high primary productivity because of the ice edge and upwelling.

More than 100 phytoplankton species have been identified from the Beaufort Sea, mostly diatoms, dinoflagellates, and flagellates. The zooplankton is dominated by herbivorous copepods; amphipods, mysids, euphausiids, ostracods, decapods, and jellyfish also are present. Kelp communities and benthic invertebrates are important components of the marine ecosystem.

Twenty-nine species of fish are regularly found in freshwater and nearshore habitats of the North Slope. Most marine species inhabit deeper offshore waters and are rarely found in the North Slope coastal zone. Marine mammals include three truly arctic species (ringed seals, bearded seals, and polar bears), and four principally subarctic species (spotted seals, walrus, beluga whales, and bowhead whales) that move into the area seasonally from the Bering and Chukchi seas.

The Human Environment

Alaska's North Slope is one of the most extreme environments in which humans live and work. The social organization of Alaska Natives centers on group subsistence activities and on an extensive network that shares subsistence harvests. Cultural knowledge and practices of North Slope Alaska Natives have been refined over many generations in an environment where one bad decision can lead to individual deaths or even to starvation of an entire village.

Initial contact with Western culture came in the mid-nineteenth century, when the area was first visited by commercial whalers and Protestant missionaries. Steady-wage jobs were first introduced with the U.S. Navy's petroleum exploration on the North Slope in the 1940s; construction of distant early warning radar sites in the 1950s also provided some employment. But even with these sources of income, wage-earning jobs on the North Slope were scarce throughout the 1950s and 1960s, and subsistence activities were the main source of food for most families.

North Slope Human Cultures in the Oil Era

The announcement in 1968 of the discovery of oil at Prudhoe Bay—the largest oil field in North America—catalyzed changes that affected the human environment of the North Slope and increasingly moved North Slope residents into the mainstream economy. The enactment of the Alaska Native Claims Settlement Act in 1971 established the Arctic Slope Regional Corporation and the village corporations. The North Slope Borough was established in 1972. The extremely rural nature of the North Slope Borough and the isolation of its small communities influence the nature and extent of the effects of oil and gas activities.

Environmental Limitations on Human Activities

The physical environment of the North Slope shapes and limits the ways that human communities operate. Agriculture and forestry are impossible; wood for construction is locally available only as driftwood in coastal areas. Most of the travel between communities on the North Slope, or between those communities and subsistence-hunting areas, occurs by air, by snow machine in the winter when the tundra is frozen, or by water in the summer. Transportation beyond the region is almost entirely by air.

The costs of transportation and of goods that must be transported to the North Slope are considerably higher than in the rest of Alaska or the continental United States. Because North Slope residents do not have greater incomes per capita than do some of their counterparts in Alaska, and those in the United States in general, they must either have a lower standard of living or rely to a greater extent on subsistence harvest, or both.

FINDINGS

The committee's unanimous findings and recommendations are presented in two sections. This one is an evaluation of major effects and how they accumulate. The next section provides recommendations for filling knowledge gaps.

Growth of Industrial Activity

Industrial activity on the North Slope has grown from a single operational oil field at Prudhoe Bay to an industrial complex of developed oil fields and their interconnecting roads, pipelines, and power lines that stretches from the Alpine field in the west to Badami in the east (Figure S-2). A highway and pipeline cross the state from near the Arctic coast. This network has grown incrementally as new fields have been explored and brought into production. For many reasons, nearly all of the roads, pads, pipelines, and other infrastructure are still in place and are likely to remain so for some time. The environmental effects of such structures are manifest not only at the "footprint" itself (the area physically covered by the structure), but also at distances that vary depending on the environmental component affected. Effects on hydrologic processes, vegetation, and animal populations occur at distances of up to a few miles (several kilometers) from the physical footprint of a structure. Effects on wildland values—especially visual ones—extend much farther, as can the effects on marine mammals of sound caused by some offshore activities. All visual effects due to the structures and associated activities will persist as long as the structures remain, even if industrial activity ceases. They will accumulate with expanded activity.

Regulatory oversight can be critical in reducing the accumulation of undesirable effects. The committee's predictions of future effects and their accumulation assume that regulatory oversight will continue at least to the extent of the recent past.

Interactions of Climate Change and Oil Development

Global and regional climates have changed throughout the Earth's history, but climate changes during the past several decades on the North Slope have been unusually rapid. Animals and plants evolve and change their ranges in response to environmental changes. Humans have migrated in and out of the area, and their cultures—including social, economic, and legal elements of those cultures—have changed as well. Those changes complicate and confound the assessment and isolation of the effects of oil and gas activities on the North Slope. If recent trends in climate continue, as many projections indicate they will, their effects will accumulate over the next century to alter the extent and timing of sea ice, affect the distribution and abundance of marine and terrestrial plants and animals, and affect permafrost. Such changes would eventually affect existing oil-field infrastructure and would continue to affect the usefulness of many oil-field technologies and how they affect the environment. Climate change also would affect arctic ecosystems and Native Alaskan cultures as well as the way they are affected by oil and gas activities. In some cases, it is relatively easy to apportion the causes of observed changes between climate or oil and gas activities; in others, it is impossible.

Damage to Tundra from Off-Road Travel

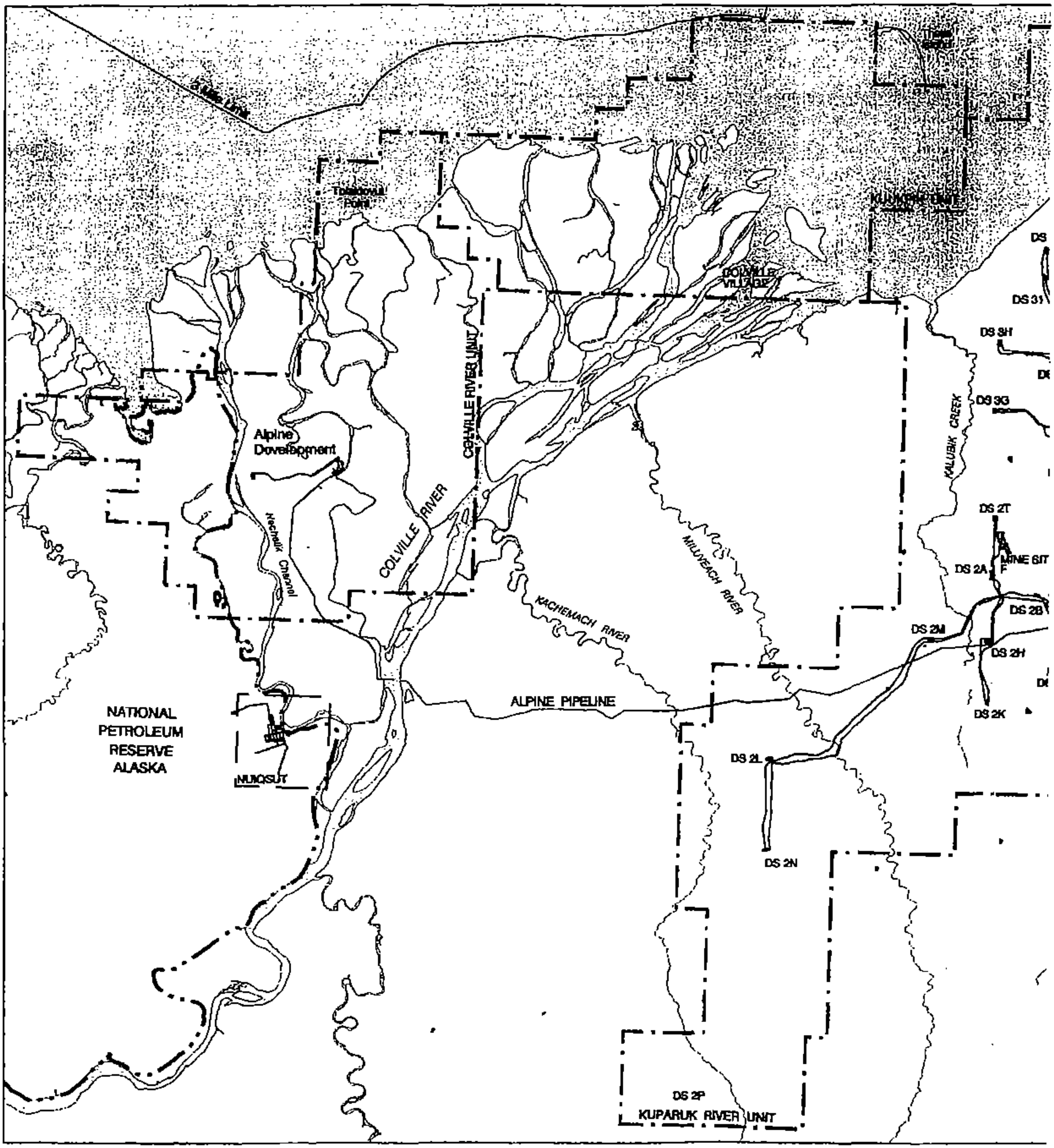
The tundra of the North Slope has been altered by extensive off-road travel. Networks of seismic-exploration trails cover extensive areas. The currently favored 3-D surveys (three-dimensional surveys that obtain geophysical data) require a higher spatial density of trails than

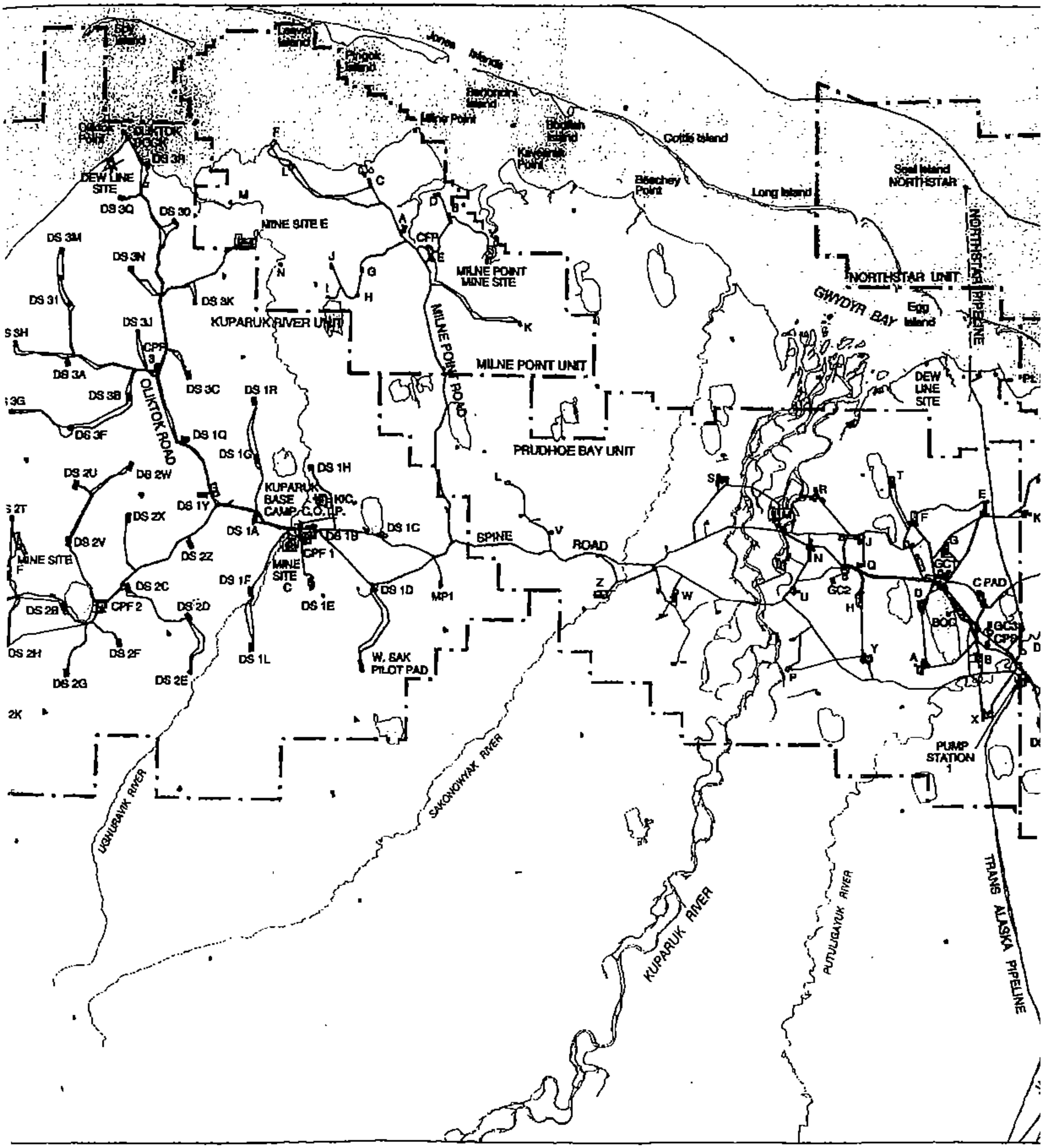
FIGURE S-2

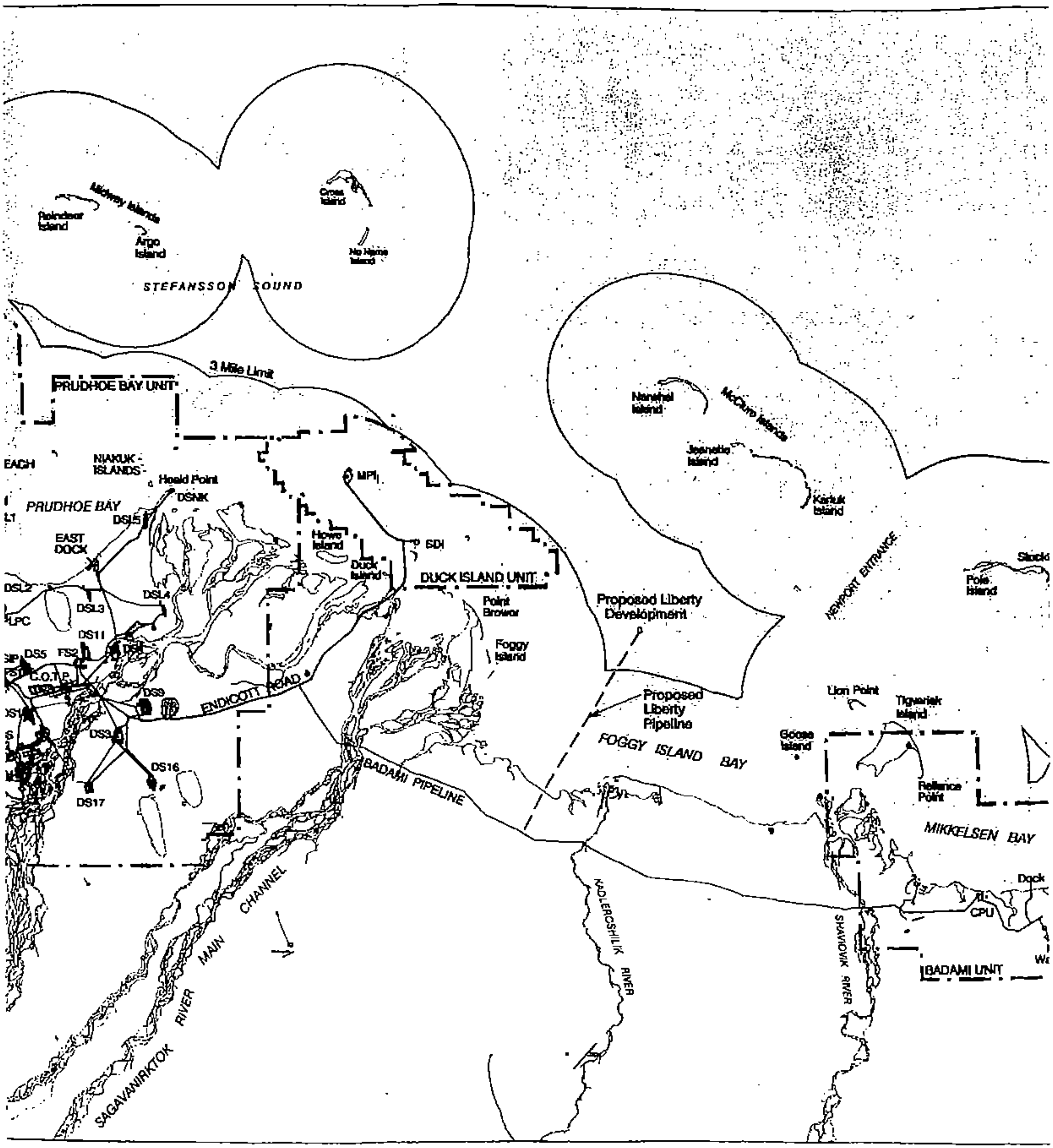
North Slope Production Facilities, Interconnecting Roads, and Pipelines

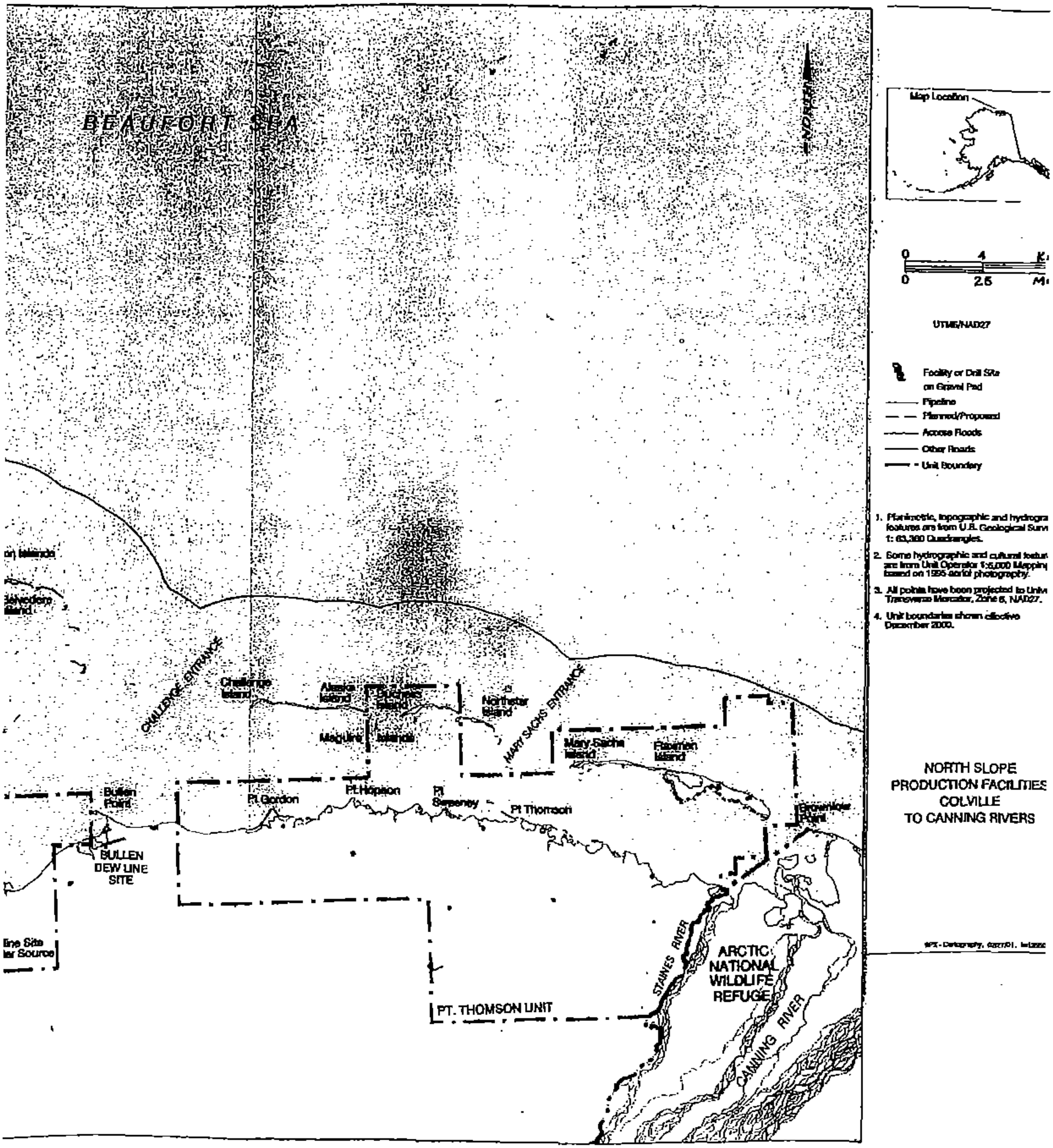
Colville to Canning Rivers

Source: BP 2001.


3 Mile Limit
COLVILLE VILLAGE
Alpine Development
Nechelik Channel
COLVILLE RIVER UNIT
COLVILLE RIVER
KACHEMACH RIVER
MILLUVEACH RIVER
KALUBIK CREEK
ALPINE PIPELINE
NATIONAL PETROLEUM RESERVE ALASKA
NUIQSUT
DS 3I
DS 3H
DS 3G
DS 2T
MINE SIT
DS 2A
DS 2B
DS 2M
DS 2H
DS 2K
DS 2L
DS 2N
DS 2P
KUPARUK RIVER UNIT


Jones Islands
Pingok Island
Milne Point
Bertoncini Island
Bodfish Island
Kavearak Point
Cottle Island
Beechey Point
Long Island
Seal Island
NORTHSTAR
Oliktok Point
OLIKTOK DOCK
DEW LINE SITE
DS 3R
DS 3Q
DS 3O
DS 3M
DS 3N
DS 3K
DS 3J
DS 3I
DS 3A
DS 3B
DS 3C
DS 3F
CPF 3
MINE SITE E
MILNE POINT MINE SITE
CPF
KUPARUK RIVER UNIT
MILNE POINT UNIT
MILNE POINT ROAD
NORTHSTAR UNIT
NORTHSTAR PIPELINE
GWYDYR BAY
Egg Island
DEW LINE SITE
PRUDHOE BAY UNIT
OLIKTOK ROAD
DS 1R
DS 1Q
DS 1G
DS 1H
DS 1Y
DS 1A
DS 1B
DS 1C
DS 1D
DS 1E
DS 1F
DS 1L
KUPARUK BASE CAMP
KIC, C.O.,I.P.
CPF 1
MINE SITE
MP1
W. SAK PILOT PAD
SPINE ROAD
DS 2U
DS 2W
DS 2X
DS 2V
DS 2Z
DS 2C
DS 2B
DS 2D
DS 2H
DS 2F
DS 2G
DS 2E
CPF 2
MINE SITE
C PAD
BOC
GC3
CPS
GC2
PUMP STATION 1
UGNURAVIK RIVER
SAKONOWYAK RIVER
KUPARUK RIVER
PUTULIGAYUK RIVER
TRANS ALASKA PIPELINE


Midway Islands
Reindeer Island
Argo Island
Cross Island
No Name Island
STEFANSSON SOUND
3 Mile Limit
PRUDHOE BAY UNIT
NIAKUK ISLANDS
Heald Point
PRUDHOE BAY
EAST DOCK
MPI
SDI
Howe Island
Duck Island
DUCK ISLAND UNIT
Point Brower
Foggy Island
ENDICOTT ROAD
Proposed Liberty Development
Proposed Liberty Pipeline
FOGGY ISLAND BAY
BADAMI PIPELINE
Narwhal Island
McClure Islands
Jeanette Island
Karluk Island
NEWPORT ENTRANCE
Pole Island
Lion Point
Tigvariak Island
Goose Island
Reliance Point
MIKKELSEN BAY
CPU
BADAMI UNIT
KADLEROSHILIK RIVER
SHAVIOVIK RIVER
SAGAVANIRKTOK RIVER MAIN CHANNEL
DS9
DS16
DS17
DS3
DS11
DSL3
DSL4
DSL2
DS5
FS2
LPC


BEAUFORT SEA
NORTH
Map Location
0 4 Km
0 2.5 Mi
UTM6/NAD27
Facility or Drill Site on Gravel Pad
Pipeline
Planned/Proposed
Access Roads
Other Roads
Unit Boundary
1. Planimetric, topographic and hydrographic features are from U.S. Geological Survey 1:63,360 Quadrangles.
2. Some hydrographic and cultural features are from Unit Operator 1:6,000 Mapping based on 1995 aerial photography.
3. All points have been projected to Universal Transverse Mercator, Zone 6, NAD27.
4. Unit boundaries shown effective December 2000.
NORTH SLOPE
PRODUCTION FACILITIES
COLVILLE
TO CANNING RIVERS
Belvedere Island
CHALLENGE ENTRANCE
Challenge Island
Alaska Island
Duchess Island
Northstar Island
MARY SACHS ENTRANCE
Maguire Islands
Mary Sachs Island
Flaxman Island
Bullen Point
Pt Gordon
Pt Hopson
Pt Sweeney
Pt Thomson
Brownlow Point
BULLEN DEW LINE SITE
STAINES RIVER
ARCTIC NATIONAL WILDLIFE REFUGE
CANNING RIVER
PT. THOMSON UNIT

earlier methods. Some effects of seismic exploration accumulate because areas have been resurveyed before the tundra recovered from the effects of previous surveys. Seismic exploration has adversely affected vegetation and caused erosion, especially along stream banks. In addition, because seismic trails are readily visible from the air, they have degraded visual experiences on the North Slope over a large area. How long damages caused by seismic surveys and other off-road travel will persist is not known, but some effects are known to have persisted for several decades.

There have been substantial improvements in technologies, especially of exploration, and the operators have been taking increased care. The technology used for obtaining seismic data continues to improve, but there is still potential damage to the tundra because of the large camps, the number of vehicles used, and the higher spatial density of 3-D trails. The new technology has reduced but not totally eliminated damage to the tundra.

Roads

Roads have had effects as far-reaching and complex as any physical component of the North Slope oil fields. In addition to their direct effects on the tundra, indirect effects are caused by dust, roadside flooding, thermokarst, and roadside snow accumulation. Roads also alter animal habitat and behavior and can increase access of hunters, tourists, and others to much of the region; enhance communication among communities; and increase contacts between North Slope communities and those outside the area.

Effects on Animal Populations.

Animals have been affected by industrial activities on the North Slope. Bowhead whales have been displaced in their fall migration by the noise of seismic exploration. The full extent of that displacement is not yet known. Some denning polar bears have been disturbed. The ready availability of new sources of food from people in the oil fields has resulted in increases in predator densities. Because brown bears, arctic foxes, ravens, and glaucous gulls prey on eggs, nestlings, and fledglings of many bird species, the reproductive success of some of those species in the developed parts of the oil fields has been reduced. Efforts to reduce the amount of supplemental food available to predators have been only partly successful, because some predators have become expert at defeating anti-predator devices, and it is difficult to persuade people to stop feeding them.

The high predation rates have reduced the reproductive success of some bird species in industrial areas to the extent that, at least in some years, reproduction is insufficient to balance mortality. Those populations—called *sink* populations—might persist in oil fields only because of immigration. Sink populations have not been unambiguously detected because census data (counts) alone do not reveal them. However, several species of birds apparently have been affected in this way.

As a result of conflicts with industrial activity during calving and an interaction of disturbance with the stress of summer insect harassment, reproductive success of Central Arctic Herd female caribou in contact with oil development from 1988 through 2001 was lower than for undisturbed females, contributing to an overall reduction in herd productivity. The decrease in herd size between 1992 and 1995 may reflect the additive effects of surface development and relatively high insect activity, in contrast to an increase in the herd's size from 1995 through 2000, when insect activity was generally low. Although the accumulated effects of industrial development to date have not resulted in large or long-term declines in the overall size of the Central Arctic Herd, the spread of industrial activity into other areas that caribou use for calving and insect relief, especially to the east where the coastal plain is narrower than elsewhere, would likely result in reductions in reproductive success, unless the degree to which it disturbs caribou could be reduced. Without specific information on the exact nature of future activity and its precise distribution, it is not possible to predict to what degree the migrations and population sizes of caribou would be affected.

Oil Spills

Major oil spills have not occurred on the North Slope or adjacent oceans through operation of the oil fields. There have been three major spills from the North Slope segment of the Trans-Alaska Pipeline. Many small spills have occurred in the oil fields, but they have not been frequent or large enough for their effects to have accumulated. The effects of a large oil spill at sea, especially in broken ice, would likely be substantial and accumulate. No current cleanup methods remove more than a small fraction of oil spilled in marine waters, especially in the presence of broken ice.

Expansion of Activities into New Areas

Seismic exploration is expanding westward into the National Petroleum Reserve-Alaska and southward into the foothills of the Brooks Range. Current technology and regulations governing seismic-exploration permits and other off-road travel have reduced but not eliminated damage to the tundra. The nature and condition of permafrost in the foothills is poorly characterized, and the hilly topography increases the likelihood that vehicles will damage vegetation, especially on knolls and riverbanks, causing increased erosion, exposing bare soil, and creating thermokarst. In addition, future exploration will be carried out in a climate that is likely to continue to warm, with milder winter temperatures and shorter periods of freezing. It is hard to predict the consequences of vehicular traffic in winter on tundra under these altered conditions.

Legacy of Abandoned Infrastructure and Unrestored Landscapes

The oil industry and regulatory agencies have made dramatic progress in reducing the effects of new gravel fill by reducing the size of the gravel footprint required for many types of facilities and by substituting ice for gravel in some roads and pads. Much less attention has been directed to restoring already disturbed sites. To date, only about 40 ha (100 acres), or about 1% of the habitat on the North Slope affected by gravel fill, has been restored. With the exception of well-plugging and abandonment procedures, state, federal, and local agencies have largely deferred decisions about the nature and extent of restoration that will be required. The lack of clear state or federal performance criteria, standards, and monitoring methods governing the extent and timing of restoration has hampered progress in restoring disturbed sites. In addition, if a site has potential for future use, restoration could make that future use more expensive or perhaps impossible, thus influencing decisions to defer restoration. Potential liability for contaminated sites also constitutes a barrier to re-use of gravel.

Because the obligation to restore abandoned sites is unclear, and restoration is likely to be expensive, the committee judges it unlikely that most disturbed habitat on the North Slope will be restored unless current constraints change dramatically. Because natural recovery in the Arctic is slow, the effects caused by abandoned and unrestored structures are likely to persist for centuries. They could accumulate further as new structures are added in the region.

Socioeconomic Changes in North Slope Communities

The North Slope Borough, the Alaska Native Claims Settlement Act, and hence the Arctic Slope Regional Corporation were created as a result of the discovery and development of North Slope oil. Without it, they would not exist or, if they did, would bear little resemblance to their current form. Oil development—and the revenue stream it created—has resulted in major, important, and probably irreversible changes to the way of life in North Slope communities. The changes include improvements in schools, health care, housing, and other community services as well as increased rates of alcoholism, diabetes and circulatory disease. There have been large changes in culture, diet, and the economic system. Many North Slope residents view many of these changes as positive. However, social and cultural shifts of this magnitude inevitably bear costs in social and individual pathology. These effects accumulate because they arise from several causes, and they interact. As adaptation occurs, the communities and the people who make them up interact in new and different ways with the causes of social change. The largest changes have occurred since the discovery of oil at Prudhoe Bay in 1968.

Interference with Subsistence Activities

Offshore exploration and development and the announcement of offshore sales have resulted in perceived risks to Inupiaq culture that are widespread and intense and are accumulating effects. The Inupiat of the North Slope have a centuries-old nutritional and cultural relationship with the bowhead whale. Most view offshore industrial activity—both its observed effects and the possibility of a major oil spill—as a threat to the bowheads and, thereby, to their cultural survival. Fall-migrating bowhead whales avoid areas where the noise from exploratory drilling and marine seismic exploration exceeds 117-135 dB. The distances over which the migratory pathways of the whales are altered are not yet known, but the deflections have forced subsistence hunters to travel farther from home to hunt whales. This increases their risk of exposure to adverse weather and the likelihood that whale tissue will deteriorate before a carcass can be landed and processed. Recent agreements to limit or move some exploration activities in the fall, which are renegotiated annually, have reduced the effects on hunters. The Inupiat view the possibility of a major oil spill as a potential catastrophe by the Inupiat, even though no such spill has occurred there. Those threats accumulate because they interact and they are repeated with each new lease sale.

Proposals to explore and develop oil resources in the Arctic National Wildlife Refuge have resulted in widespread, intense perceived risks to Gwich'in culture that themselves are accumulating effects. The Gwich'in Indians of northeast Alaska and northwest Canada have a centuries-old nutritional and cultural relationship with the Porcupine Caribou Herd. Most Gwich'in oppose any oil development that would threaten the herd, especially on its calving ground, and, thereby, threaten their cultural survival. This threat accumulates, because repeated attempts to develop areas used by the herd have occurred and probably will continue to occur.

Aesthetic, Cultural, and Spiritual Consequences

Many activities associated with oil development have changed the North Slope landscape in ways that have had accumulating aesthetic, cultural, and spiritual consequences. They have reduced opportunities for solitude and have compromised wildland (wilderness) and scenic values over large areas. They also violate what some Alaska Natives call the "spirit of the land," which they describe as central to their relationship with the land. Those consequences have increased in proportion to the area affected by development, and they will persist as long as the landscape remains altered. They will accumulate further if the area affected by development increases.

Response of North Slope Cultures to Declining Revenues

The current, altered way of life of North Slope communities will be impossible to maintain unless enough money continues to come into those communities from outside sources after oil and gas activities cease. But likely continuing sources of funds appear to be modest. Painful adjustments to reduced financial resources can and probably will be postponed for as long as oil and gas are being extracted, but eventual adjustment is unavoidable. The nature and extent of adjustment will be determined by the adaptations North Slope societies have made to the cash economy made possible by oil and gas and other activities.

FILLING KNOWLEDGE GAPS

A great deal of time and effort had been invested in studying North Slope environments and assessing the effects of oil and gas activities there. Some of the research recommendations that follow are for new investigations, but many of them represent a sharpening of the focus and the emphasis of current research efforts.

To the degree possible, information on the effects of industrial development on the North Slope (including information on the physical, biotic, and human environments) should be gathered concurrent with oil and gas activities so as to take advantage of opportunities for learning, and to promote better management (i.e., adaptive management).

Need for Comprehensive Planning

Decisions about where, when, and under what conditions industrial activities are permitted on the North Slope are made by many federal, state, municipal, and other agencies. Communication among them has usually been weak and sporadic. Decisions generally have been made on a case-by-case basis, without a comprehensive plan and regulatory strategy that identifies the scope, intensity, direction, and consequences of industrial activities judged appropriate and desirable. The anticipated high costs to dismantle and remove infrastructure and to rehabilitate and restore the North Slope environment raise concerns about the availability of funds for restoration when production ends. For these and other reasons, comprehensive planning is needed. All comprehensive plans are necessarily provisional and will need to be revised as new information becomes available. Nonetheless, a comprehensive framework and plan should be developed for the North Slope so that decisions can be evaluated with respect to their compatibility with overall goals, the likely effects of individual activities on all receptors that might be affected by them, and the likelihood that the activities will result in undesirable effects that are long-lasting or difficult to reverse. The plan should include all phases of oil and gas activity, from lease sales, to dismantlement and removal of infrastructure, to environmental rehabilitation and restoration. The plan also should identify areas for research.

Ecosystem Research

Most ecological studies in the Prudhoe Bay region have been local; ecosystem-level research has largely been lacking. Although ecological communities within an oil field are likely to differ from similar unaffected communities elsewhere, the extent and nature of the differences are largely unknown. To assess those differences, researchers should be given access to protected areas inside and outside the industrial complex. Particular research attention should focus on the ecological processes most likely to be altered by industrial activities.

Offshore Oil Spills

Although no large oil spills have occurred in marine waters off the North Slope, their potential is such a major concern that the committee recommends research into mitigating their effects. Such research would help refine assessments of the accumulation of effects of a major spill in that environment. This committee did not attempt to reach consensus on whether, when, and how experimental oil spills might be used in a research program. Other research seems to be warranted, however, including on possible ways of deflecting bowhead whales and perhaps other marine mammals from spill-affected areas, and on the effectiveness and environmental liabilities and advantages of nonmechanical methods of cleaning up oil spilled in the sea (dispersants, in-situ burning), especially in broken ice.

Zones of Influence

The effects of industrial activities are not limited to the footprint of a structure or to its immediate vicinity; a variety of influences can extend some distance from the actual footprint. They range from the effects of gravel roads and pads on animals, which can extend for several miles from the footprint, to the influence of industrial structures on wilderness values, which can extend much farther. The full accumulation of effects of oil and gas activities to date, as well as future accumulation, cannot be assessed without better quantitative information about the ways in which various kinds of effects extend for various distances.

Human Communities

The communities of the North Slope have not been adequately involved in most research in the region. As a result, some important information concerning accumulated effects is missing or sparse. To improve the assessment of effects and their accumulation, research on the North Slope should be a cooperative endeavor with local communities. Traditional and local knowledge includes rich and detailed information about many aspects of the environment. Balancing economic benefits of oil and gas activities against loss of traditional culture often is a dilemma for North Slope residents. Research should be conducted to better characterize the specific benefits and threats that North Slope residents perceive are posed to their way of life and health by oil and gas activities. The studies should attempt to separate the effects of oil and gas activities from other causes of socioeconomic change. Research should seek to establish how oil and gas activities have affected the behavior of communities and individuals. Research should be done to identify the direct and indirect monetary rewards and costs—including non-use values such as existence and bequest values—associated with petroleum development on the North Slope.

Human-Health Effects

Human-health effects of oil and gas activities have not been well documented. Although some problems on the North Slope—increased use of alcohol and drugs, increased obesity, and other societal ills—are evident, it is not possible to say with the limited data available to what degree they are the direct result of oil and gas activities. Other concerns are widespread among Native residents of the North Slope. The degree to which increased financial resources related to oil have balanced adverse effects by improving the quality and accessibility of local medical care is unknown. These questions are in great need of additional reliable information.

Air Contamination and its Effects

Air pollution is a concern to many North Slope residents. Little research has been done to quantify the effects of air pollution on the North Slope or to determine how local and regional air masses interact. Air-pollution monitoring has been limited to priority pollutants from 1986 through 2002 at a few sites. Not enough information is available to provide a quantitative baseline of spatial and temporal trends in air quality over long periods across the North Slope. Given local concerns about air quality and the perception that poor air quality is affecting the public health, research and monitoring should be implemented to distinguish between locally derived emissions and long-range transport of air contaminants to determine how they interact, and to monitor potential human exposure to them.

Off-Road Traffic and the Tundra

Networks of seismic trails and trails of other off-road vehicles, ice roads, and ice pads cover large areas of the tundra. They cause concern because of the damage they do to vegetation and because of their visibility from the air. Continuing advances in the technology of seismic-data acquisition might reduce its effects by reducing the weight, tracks, or number of vehicles used, but the degree to which this will happen is not known because the effects of the new technologies have not yet been extensively studied.

Studies are needed to assess the long-term visibility of seismic trails from the air. Research also is needed to determine the amount of snow cover and the frost penetration required to adequately protect the tundra from the effects of seismic exploration and the use of Rolligons (low tire-pressure off-road vehicles) and other off-road vehicles. New areas where oil and gas exploration are likely to occur differ substantially from current areas. Characterization of those environments should include descriptions of topography; permafrost conditions; sand, gravel, and water availability; hydrological conditions; and biotic communities.

Caribou and Bowhead Whales

A better understanding is needed of the seasonal habitat requirements of caribou, natural environmental constraints that affect their reproductive physiology and movements, their vulnerability to natural disturbance, and how anthropogenic disturbance affects them at various time of the year in the Arctic.

Studies are needed to determine the qualitative relationship between the noise generated by offshore operations and the migratory and acoustic behavior of bowhead whales. The studies should include analysis of the effects of multiple noise sources. Better information is also needed about the degree to which bowheads feed in the Alaskan portion of the Beaufort Sea.

Consequences of Water Withdrawals

Water for ice roads and pads and for other purposes is taken from lakes on the North Slope. Water depth has a great influence on the distribution of fish in coastal-plain lakes because lakes shallower than 1.8 m (6 ft) freeze to the bottom in winter. Because most lakes in the existing development area, between the Colville and Sagavanirktok rivers, are shallower than 1.8 m, few fish are present and effects have been minimal. As development spreads into regions with deeper lakes, such as the Colville delta and the eastern portion of the National Petroleum Reserve-Alaska, there is a greater chance that fish populations will be affected.

The current regulatory criterion, which allows 15% of the minimum winter water volume to be removed from fish-bearing lakes, should be studied to determine its ability to prevent loss of fish and invertebrates. A study of the effects of withdrawing water from lakes that do not contain fish should also be conducted to assess the degree to which current water use affects the biota associated with those bodies of water.

Dealing with Uncertainty

Actions undertaken to identify and reduce the undesirable effects of interactions among perturbations and receptors should greatly improve the quality and quantity of data for future decision-making. However, for several reasons it is unreasonable to expect that sufficient data will ever be available to meet all needs for information. Some animal species, such as marine mammals and fishes, are intrinsically difficult to study. Detecting even fairly large changes in their population densities and other demographic characteristics could be impossible no matter how much money is allocated for research. Also, adequate experimental controls could be impossible to establish.

Whenever a statistical test is performed to assess an environmental effect, the magnitude of the effect that could have gone undetected should be explicitly stated. Those uncertainties should be communicated clearly to decision makers.

THE ESSENTIAL TRADE-OFF

The effects of North Slope industrial development on the physical and biotic environments and on the human societies that live there have accumulated, despite considerable efforts by the petroleum industry and regulatory agencies to minimize them. To the best of its ability, and given the time, data, and resources available, the committee has identified those effects. It has also attempted to assess how effects are likely to accumulate with future expansion of industrial activities into new areas. Continued expansion is certain to exacerbate some existing effects and to generate new ones—possibly calling for regulatory revisions. Whether the benefits derived from oil and gas activities justify acceptance of the inevitable accumulated undesirable effects that have accompanied and will accompany them is an issue for society as a whole to debate and judge. However, if wise decisions are to be made, the nature and extent of undesirable effects likely to accompany future activities must be fully acknowledged and incorporated into regulatory strategies and decision-making. We hope this report will assist in the process.

1

Introduction

In 1968, large oil reserves were discovered along the coast of Alaska's North Slope. The oil field in Prudhoe Bay (Figure 1-1) is now the largest in North America. It is estimated that approximately 23 billion bbl (966 billion gal or 3.7 trillion liters [L]) of oil originally was in the ground. Production began in 1977. Since that initial discovery, other large fields have augmented the production from Prudhoe Bay. By the end of 2002, about 14 billion bbl (588 billion gal, 2.2 trillion L) of crude oil had been produced. North Slope oil has averaged about 20% of U.S. domestic production since 1977, and it currently provides about 15% of the annual domestic production of approximately 3.3 billion bbl and 7% of the annual domestic consumption of approximately 7 billion bbl. Reliable estimates of technically recoverable reserves for the North Slope and its adjacent offshore areas are not currently available. There also are huge reserves of coal and natural gas in the region, and if production of those resources were to become economically feasible, the strategic and economic importance of the hydrocarbon energy resources of the region would be even greater.

The term North Slope refers to the area from the crest of the Brooks Range to the Arctic Coast, from the Canadian border to Point Hope. Although the area is more correctly called the *Arctic Slope*, the Committee on Cumulative Environmental Effects of Alaskan North Slope Oil and Gas Activities has elected to follow convention and use *North Slope* in this report.

The benefits brought by oil and gas production on the North Slope have come with environmental concerns and consequences. One of the earliest major environmental impact statements (EISs) was a 6-volume effort (DOI 1972) that examined the effects of the Trans-Alaska Pipeline. As production on the North Slope increased, many other studies and EISs have been produced, and knowledge of the effects of oil and gas exploration and development has increased substantially. Environmental concerns about exploration and development on the North Slope have focused on many subjects, including but not limited to the following:

- the effects of structures on the migration of fish and large mammals, especially caribou
- the effects on the tundra of off-road travel
- the effects on bowhead whales and other marine mammals of seismic exploration and industrial noise
- the risk of toxic contamination of fish, wildlife, and plants used for food by Alaska Natives
- the effects of roads (both gravel and ice)
- the effects of oil spills on terrestrial, marine, and coastal ecosystems and on the humans that depend on them

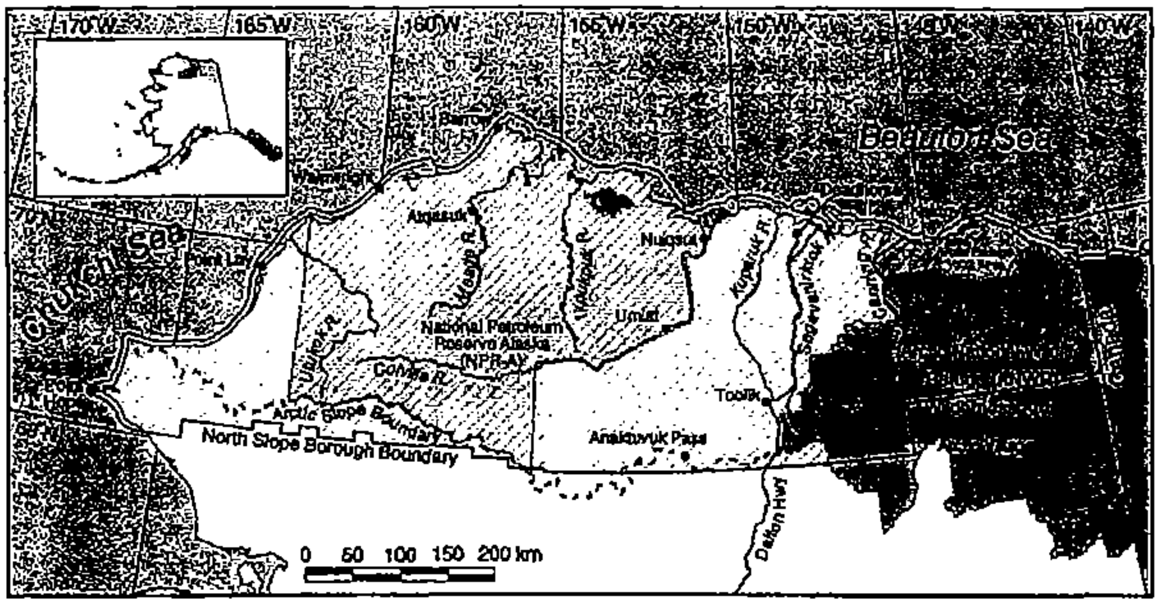


FIGURE 1-1. The Alaska North Slope region. The dashed line is the southern boundary of the drainage basin. The Trans-Alaska Pipeline is close to the Dalton Highway. Source: Alaska Geobotany Center, University of Alaska Fairbanks 2002.

- the effects on a variety of ecosystems of transportation of material, supplies, and people
- the extent to which effects are reversible
- whether remediation is possible and will actually be undertaken

Concerns have also focused on social consequences, such as the effects of new roads and access to formerly isolated communities; the socioeconomic effects of jobs related to oil and gas development; the effects on subsistence practices, either as a result of the introduction of a wage economy or because of environmental change; and loss of wildland and wilderness values.

There is an extensive research literature on the actual and potential effects of oil and gas activity on the North Slope's physical, biotic, and human environments (e.g., BP 1991; Engelhardt 1985a; Kruse et al. 1982; Loughlin et al. 1994; MMS 1990, 1991, 1992; Truett and Johnson 2000; Walker et al. 1986a, 1987a,b). Much of this work has been sponsored by the Outer Continental Shelf Environmental Assessment Program (OCSEAP) of the National Oceanic and Atmospheric Administration and the Department of the Interior, and by OCSEAP's successor, the Environmental Studies Program of the Department of the Interior. Additional research has been funded by the U.S. Army, the National Science Foundation, the Geological Survey the Fish and Wildlife Service of the Department of the Interior, and the Department of Energy. Many studies have been performed and funded by the oil industry and university researchers have contributed a large amount of information about the region. Despite the considerable research since the 1960s to assess the effects of oil and gas exploration, development, and production, no integrated, comprehensive analysis of cumulative impacts has been attempted. Understanding the cumulative effects of oil and gas development at a variety of locations over time is critical to informed, long-term decision-making about resource management.

THE PRESENT STUDY

In 1999, the U.S. Congress asked the National Research Council for assistance in addressing this gap in understanding (U.S. Congress: Conf. Rept 106-379 [H.R. 2684] Fiscal Year 2000 Appropriations for the Environmental Protection Agency). In response, the Council established the Committee on Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope and charged it with providing a comprehensive analysis, including conclusions and recommendations (Box 1-1).

Although the cumulative effects of North Slope oil and gas activities—especially production—extend beyond the region, the committee's focus was confined to Alaska's North Slope and as far into the Arctic Ocean as there is evidence of environmental effects. As a result, the committee did not consider releases of compounds that could affect global atmospheric chemistry or the contribution of the burning of North Slope oil to global climate warming. The contribution of North Slope oil and gas activities to the accumulation of such atmospheric effects is small on a global basis. Climate change is considered as it interacts with the effects of oil and gas activities on the North Slope.

The committee's 18 members, who are experts in a wide range of disciplines (see Appendix K), met 8 times over the course of the study. The committee relied on its members' expertise, on an extensive review of the literature, and on information gathered from public meetings held throughout the state. Meetings and site visits were held in Alpine, Anchorage, the Arctic National Wildlife Refuge, Arctic Village, Endicott, Fairbanks, Kaktovik on Barter Island, and the Prudhoe Bay oil field. Appendix A lists those who made presentations and otherwise assisted the committee.

Box 1-1 Statement of Task

The Committee on Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope was charged to review information about oil and gas activities (including exploration, development, and production) on Alaska's North Slope and assess the known and probable cumulative effects on the physical, biological, and human environments of Alaska's North Slope (including the adjacent marine environment) of oil and gas activities there from the early 1900s to the present, including cleanup efforts. The committee was asked to provide an assessment of potential future cumulative effects, based on its judgment of likely changes in technology and the environment, on a variety of scenarios of oil and gas production volumes, and in combination with other probable human activities, including tourism, fishing, and mining. As part of its report, the committee was charged to describe and document its methodology for assessing cumulative effects and identify gaps in knowledge and make recommendations for future research needed to fill those gaps. Although cumulative effects of oil and gas activities occur beyond the North Slope (e.g., related to transportation and ultimate combustion), the committee was asked to confine its focus to the North Slope (i.e., north of the crest of the Brooks Range) and as far into the Arctic Ocean as there is evidence of environmental effects.

UNDERSTANDING AND ASSESSING CUMULATIVE ENVIRONMENTAL EFFECTS

The ecologist W.E. Odum wrote (1982) that when numerous small decisions about related environmental issues are made independently, the combined consequences of those decisions are not considered. As a result, the patterns of the environmental perturbations or their effects over large areas and long periods are not analyzed. This is the basic issue of cumulative effects assessment. The general approach to identifying and assessing cumulative effects evolved after passage of the National Environmental Policy Act (NEPA) of 1969, and the committee has followed that approach.

Although the NEPA requires EISs for many major projects, if those projects are considered separately from similar projects or in isolation from different kinds of projects in the same area, some of their effects—their cumulative effects—are likely to be missed. In 1978, the Council on Environmental Quality promulgated regulations implementing the NEPA that are binding on all federal agencies (40 CFR Parts 1500-15081 [1978]). A cumulative effect was defined as "the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions. . . . Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time." For example, an EIS might conclude that the environmental effects of a single power plant on an estuary might be small and, hence, judged to be acceptable. But the effects of a dozen plants on the estuary are likely to be substantial, and perhaps of a different nature than the effects of a single plant—in other words, they are likely to accumulate. Even a series of EISs might not identify or predict that accumulation to produce those more serious or different effects that result from the interaction of multiple activities. Cumulative impact assessment (CIA) arose to address such considerations.

In interpreting the broad charge of assessing cumulative effects, the committee focused on whether the effects under consideration interact or accumulate over time and space, either through repetition or combined with other effects, and under what circumstances and to what degree they might accumulate. As an example, consider a repeated environmental insult that is localized in space and occurs so infrequently that natural processes of recovery or human efforts can eliminate its effects before another insult occurs. In this case, one would conclude that the effects of the insult do not accumulate (rather than concluding that the insult is not "a cumulative effect"). This approach also directs attention to the circumstances under which effects might accumulate.

The accumulation of effects can result from a variety of processes (NRC 1986). The most important ones are:

- *Time crowding*—frequent and repeated effects on a single environmental medium. This would be the case, for example, if repeated oil spills occurred on an area of tundra before that area had recovered from previous spills. Time crowding also can result if there are long delays before the effects of an action are fully manifest. An increase in the melting of permafrost might not become apparent until decades after the actions that caused it were initiated.
- *Space crowding*—high density of effects on a single environmental medium, such as a concentration of drilling pads in a small region so that the areas affected by individual pads overlap. Space crowding can result even from actions that occur at great distances from one another. For example, air pollution from temperate latitudes can interact with local sources of contamination to increase atmospheric haze on the North Slope.
- *Compounding effects*—synergistic effects attributable to multiple sources on a single environmental medium, such as the combined effects of gaseous and liquid emissions from multiple sources on a single area, or nonlinear effects, or interaction of natural and anthropogenic effects, such as the *Exxon Valdez* oil spill and El Niño events.
- *Thresholds*—effects that become qualitatively different once some threshold of disturbance is reached, such as when eutrophication exhausts the oxygen in a lake, converting it to a different type of lake.
- *Nibbling*—progressive loss of habitat resulting from a sequence of activities, each of which has fairly innocuous consequences, but the consequences on the environment accumulate, for example by causing the extirpation of a species from the area.

These examples illustrate why recognizing and measuring the accumulation of effects depends on the correct choice of domain—temporal, spatial—for the assessment. If the time domain chosen to analyze the effects of a power plant on an estuary is the plant's period of operation and the space domain is that covered by its exhaust plume, then the accumulation of the effects of multiple plants will be missed if a series of EISs analyzes each plant in isolation. Alternatively, if the space domain is the entire estuary, and the time domain is long enough to include the commissioning of several plants, then at least some accumulation of effects is likely to be detected. Effects typically accumulate as the result of repeated activities of similar or different types. However, in some cases the effects of a single action or event can accumulate. This is especially true if the effects persist for a long time and are added to by the effects of other activities, with the result that there is a change from what would have resulted if the single event had not occurred.

Although the assessment of cumulative effects has a history of several decades (e.g., NRC 1986), it is still a complex task. The responses of the many components of the environment (receptors) likely to be affected by an action or series of actions differ in nature and in the areas and periods over which they are manifest. An action or series of actions might have effects that accumulate on some receptors but not on others, or on a given receptor at one time of the year but not at another. Therefore, a full analysis of how and when effects accumulate requires multiple assessments.

To address this problem the committee attempted to identify the essential components of a such an assessment:

- Specify the class of actions whose effects are to be analyzed.
- Designate the appropriate time and space domain in which the relevant actions occur.
- Identify and characterize the set of receptors to be assessed.
- Determine the magnitude of effects on the receptors and whether those effects are accumulating.

These criteria cannot always be applied because of data limitations. As will become apparent later in this report, the effects of individual actions range from brief or local to widespread, long-lasting, and sometimes irreversible.

At the most general level, the class of actions considered by the committee encompasses all of those associated with oil and gas development. The spatial domain is the North Slope of Alaska and its adjacent marine waters. The temporal domain is 1965 to 2025, or in some cases 2050, and the receptors are the physical, biological, and human systems in the region.

The committee conducted analyses of specific activities (e.g., seismic exploration, road building, gravel mining), and determined their most significant effects (individual or collective) on specific receptors (e.g., tundra vegetation, species of special concern, subsistence hunting, employment).

A particularly challenging problem is to determine the area over which the effects of an activity, such as building a drilling pad, a road, or a seismic survey trail, are felt. Some analyses measure the effects of an activity by its "footprint"—the physical area covered by a drilling pad or road, for example—although the effects can extend well beyond that space. The effect of a road extends beyond the actual physical area where the gravel smothers vegetation. Large vehicles make noise that can frighten wildlife some distance from the road; they raise dust that settles downwind, affecting the timing of snow melt and thus the underlying vegetation. Roads also impede drainage. A highway can increase access and thus bring hunters to an area. All of these effects can be defined and measured.

To conduct an analysis of how effects accumulate, one must understand what would occur in the absence of a given activity. The accumulated effects are the difference between that probable history and the actual history or projected effects of the action. Such analyses are most readily accomplished if good baseline data are available or if data are available about the same kinds of receptors in similar areas that are not influenced by comparable actions. In some cases, the lack of such information prevented the committee from identifying and assessing possible effects of some activities.

In estimating the accumulation of effects it is customary to assume that the only source of environmental change is the action under study, and that the environmental setting itself has no bearing. There is a challenging complication in the Alaskan Arctic, however, because the climate is expected to warm so rapidly that the effects of current activities could be much greater on the permafrost landscape than would be the case if the climate were relatively stable.[1] The committee's prediction of the accumulation of effects over several decades has been limited by ignorance of the details of how this climate change will proceed and thus of its potential effects on North Slope ecosystems.

Even if accumulating effects are identified, their magnitude and their biological, economic, and social importance must be assessed. Discontinuities or inflection points in biotic or social relationships, a change in some important process, or the widespread perception of members of an affected community of the importance of some change are generally associated with environmentally or socially important effects. The committee assessed biotic and social importance separately for each receptor.

Although the committee was directed to evaluate the cumulative effects of oil and gas activities on the North Slope, the accumulation of physical, biotic, and human environmental effects of those activities extends beyond the region. Moreover, activities elsewhere in the world influence what happens to the North Slope environment. Although the committee followed its charge and concentrated attention on the North Slope, external effects had to be considered in situations where they combine with activities on the North Slope to influence the nature and extent of environmental effects there.

SOURCES OF KNOWLEDGE

Information about Alaska's North Slope, the functioning of its human communities and ecosystems, and the effects of industrial activities during the past century comes from many sources, including peer-reviewed literature, government reports, and industry documents. The committee made a special effort to evaluate and incorporate the traditional and local knowledge of residents of the North Slope. People have lived on the North Slope since long before industrial activity began, and because they have had intimate, sustained contact with the immediate environment, they provide a unique source of knowledge. The committee did not compare the North Slope with the Russian experience because—despite some environmental similarities—environmental laws and regulations, societal factors, and economic systems are very different from Alaska's, and because reliable information is not easy to obtain.

Despite the evident value of the traditional and local knowledge of Alaska Natives, their insights have been poorly incorporated into the overall public perception, both on and off the North Slope, about cumulative changes and their causes. The reasons for this failure are generally understood (Box 1-2, Appendix H), but the problem is still largely unresolved (but see

[1] The largest contributor to climate warming is the burning of fossil hydrocarbon fuels. Although the resultant climate change affects the North Slope—probably more than lower-latitude areas—this effect is not considered as an effect of North Slope oil and gas activities in this report because the North Slope provides only a small fraction of all the fossil hydrocarbons burned on earth. However, it is an important factor that must be considered in all analyses of this type.

Kofinas et al. (2002) and Huntington (2000) for descriptions of incorporation of traditional knowledge into research on environmental change in the Arctic).

Box 1-2 Why Answering Why is Difficult: Reconciling Alaska Native Observations of Environmental Change with Western Science

Alaska Native hunters from the Arctic region have told the committee about changes in the character of seal skins—some are thinner (almost translucent) than in the past and they no longer crimp as readily when they are shaped into soles for mukluks (boots). In other locales, Alaska Natives also have observed other changes: There are unusual sores and lesions on fish, moose, and caribou. There is a change in the taste and color of the local tea. Caribou meat tastes different. People in their villages are suffering from increased respiratory diseases. Communities ask why the changes are occurring, and local opinion often finds blame in industrial development.

There is little in the way of scientific data to shed light on such questions and anomalies, and anecdotal evidence is difficult for scientists to study or explain. Because some of the questions are about subtle changes in small areas or for short periods, and because examining those issues could require unattainable investment of research resources, some of the questions could be unanswerable. There also are few predevelopment data to use for comparison. And there might be no way to distinguish which factors contribute given effects (and in what combination), or whether the changes can be attributed to natural variability, climate change, oil and gas development, modernization, or other human or natural influence.

The seal-skin observations are difficult to study, for example, because they occur in isolated instances and it would be difficult (if not impossible) to do the sampling and measurements necessary to obtain meaningful data. Socioeconomic questions are even more perplexing: Could research help explain what proportion of significant social problems—alcohol and drug abuse, domestic violence, health problems—is attributable to oil and gas development or to other forces of cultural disruption?

No relevant data or plausible mechanisms have been identified to relate changes in seal-skins to oil and gas development. But that example is just one illustration of repeated Alaska Native concerns about changes in the environment for which explanations are sought. And local concerns at times are difficult for outsiders to understand because visitors usually lack the intimate, even spiritual, relationship Alaska Natives have with their environment.

Improving the ways science addresses the issues important to Alaska Native communities affected by development on the North Slope is a problem far bigger than this report can address. This much is clear: A better mechanism is needed to increase Alaska Native input into the research process; some way by which they can be involved in translating their observations into hypotheses that can be addressed by research, and some means to ensure that Alaska Natives become partners in the research. Appendix H describes some of these difficulties and approaches to resolving them.

Most cross-cultural collaborations have been informal and occur on a case-by-case basis. They often begin because of the interest and commitment of individual researchers who have no special training in working across cultures. There are few policy directives and only limited financial support for use of traditional and local knowledge or for researchers to engage in cross-cultural awareness and communication orientation programs. Consequently, institutional commitment to understanding and using traditional and local knowledge for stewardship and research has been subject to shifts in emphasis as governments change. Those shifts are a source of frustration and distrust for Alaska Natives who have to undertake extensive and costly efforts to educate new administrators, policy-makers, and managers each time they change.

Scientists find it difficult to assess the quality and spatial scales of relevance of much traditional knowledge, so it is difficult to determine whether the observations offered by any Alaska Native collaborator are valid. Alaska Natives, for their part, have told the committee that they are sometimes skeptical of the scientific motivations to acquire information and thus can be reluctant to cooperate or participate. Moreover, they are rarely involved in the formative stages of collaborative research, and for the most part they are not involved in the actual research efforts. In addition, many Alaska Native elders, who are potentially important sources of information, do not speak English fluently or at all, and they are not schooled in communicating with Western culture, thus diminishing the value of any information exchanges that may occur. Traditional and local knowledge can provide useful, qualitative information to scientists and an early warning system for identifying emergent biological or environmental trends and anomalies in local, regional, or ecosystem-wide geographical areas. For example, Alaska Natives in the Arctic have reported changes in migration patterns of the bowhead whale, changes in the thickness and elasticity of seal skins, and changes in the taste and color of "Eskimo tea." Many changes in wildlife are apparent only to people who interact with the animals regularly; scientists who do not eat the local diet would not know, for example, that the taste of seal meat has changed—no matter how much research has been conducted. If communication and collaboration were improved, traditional and local knowledge could provide scientists with new and timely hypotheses to pursue in their search for the causes of wildlife declines.

Traditional and local knowledge can influence many aspects of research, but better and more systematic ways to access and use this information must be developed if that value is to be realized (e.g., Huntington 2000). The process must consider, among other things, issues of communication protocols, dispute resolution, and information exchange; appropriate use of information; protocols for attribution of information sources; compensation for research collaborators; community relations; and cross-cultural communications and cultural-awareness training. The failure to seek and use traditional and local knowledge can have far-reaching consequences, including the loss of time and resources. The assessment of changes in the bowhead whale population is one instance in which traditional knowledge has been incorporated into the design and conduct of a major, long-term research effort (Albert 2001).

Bowhead Whales

Estimating population size for the Bering Sea bowhead population became a priority in the mid- to late 1970s when there was increasing concern in the International Whaling Commission (IWC) that the subsistence harvest in Alaska was unduly pressuring the stock. At the same time, there was growing interest in offshore petroleum development. All of this prompted the National Marine Fisheries Service (NMFS) of the U.S. Department of Commerce to undertake a population estimate. In 1976 and 1977 observers were placed at the seaward edge of the shore-fast ice near Point Barrow, where the passing whales came close to shore. Their data suggested a population of 600–2,000 whales (Tillman 1980). Data from 1978 and 1979 (Branham et al. 1980), which included ice-based and aerial surveys, yielded an estimate of 1,783-2,865 (mean 2,264) whales (Braham et al. 1980). The numbers were so low that the IWC initially set a 1978 harvest quota of zero whales. However, a revised quota of 12 landed or 18 struck was set after a special IWC meeting was called by the United States. This experience alarmed bowhead-dependent communities in Alaska, who believed their hunt was being unduly restricted because the whale counters were not counting the whales accurately (Albert 2001).

In the early 1980s, the responsibility for estimating bowhead population size was transferred to the people of northern Alaska. By then, a substantial difference had developed in views between the Alaska Native hunters and most scientists familiar with the bowhead issue. The "scientific wisdom" of the late 1970s was that the northward migrating bowhead whales traveled primarily in elongated open areas (leads) in the deteriorating and drifting ice, and that most of the passing whales could be counted by observers at the seaward edge of the shore-fast ice.

Alaska Native hunters cited their own observations, as well as information handed down through the generations, that bowheads passing Point Barrow move on a broad front (to about 20 km [12 mi] wide) and are not restricted to large areas of open water. They also move through areas of broken ice and heavy ice, not just through areas of open water, and they use their heads to fracture ice from below to produce small breathing holes that are easily missed by observers (Albert 1996, 2001; George et al. 1989). The Natives therefore believed that the population estimate of 2,000 animals was far too low.

Those comments were considered by scientists of the NMFS and others and a multiyear counting program was designed to assess them. The new census used both ice-based visual observations and acoustical techniques to help detect passing whales. During the spring field season of 1984 the use of passive acoustics—used to locate calling whales at distances of 16-19 km (10-12 mi)—was fully integrated into the census (Clark et al. 1985, Dronenburg et al. 1986).

To correlate the number of calls with the number of passing whales, a tracking algorithm linked a sequence of acoustic locations, visual sightings, or both to form a whale track (Ellison et al. 1987, Ko and Zeh 1988, Sonntag et al. 1986). The acoustical techniques, the associated tracking algorithm, and the related complex statistical analysis allow the visual and acoustic data to be combined (Clark et al. 1996; Clark and Ellison 1988, 1989; Sonntag et al. 1986; Zeh et al. 1990) to produce more accurate population estimates. Those estimates are submitted annually to the IWC's Scientific Committee for rigorous peer review. During the 1987 Scientific Committee meeting, that group agreed to a best estimate of 7,200 whales (2,400 standard error) (Gentlemen and Zeh 1987, IWC 1988, Zeh et al. 1988). Over the next several years, as the tracking algorithm, acoustic techniques, and statistical techniques were refined, the population size estimate became more precise and the harvest quota increased. By 1996, the IWC-accepted estimate was 8,200 whales (with a 95% confidence interval from 7,200 to 9,400) (IWC 1997, Raftery and Zeh 1998). The estimated annual rate of increase (after hunting removals) from 1978 to 1993 was 3.2% (with a 95% confidence interval of 1.4-5.1) (Raftery and Zeh 1998).

Thus, after many years of intensive study, the assertions of Alaska Native hunters were verified (Albert 2001). This prolonged and continuing effort is one significant instance in which several aspects of traditional knowledge have been confirmed by scientific study and have been used in management decisions.

REPORT ORGANIZATION

Chapters 2 and 3 set the stage by describing the human, physical, and biotic environments of Alaska's North Slope. They are not intended to be exhaustive. They present only enough information for a general overview. Chapter 4 provides the history of oil and gas activities on the North Slope. It includes brief descriptions of how oil is found, extracted, and transported, and it describes the physical infrastructure of North Slope oil fields. It ends with descriptions of recent technological advances and of how oil and gas activities can affect the environment. Chapter 5 is the committee's analysis of a plausible scenario of future industrial activity that assumes continued exploration and production. It provides the basis for the committee's predictions of how the effects of oil and gas activities might accumulate in the future.

Chapters 6-9 treat the physical environment, plants, animals, and humans, respectively, as receptors of environmental effects. Those chapters present the committee's assessments of the effects to date and the degree to which they have accumulated, and their potential to accumulate in the future. The committee also identifies some effects that appear not to have been serious or to have accumulated to date. Each chapter includes a summary of the committee's findings and research recommendations. Chapter 10 describes knowledge gaps and recommends research; Chapter 11 summarizes the committee's findings about major cumulative effects.

A series of appendixes provides additional detail on a variety of topics. They include information on committee meeting places, dates, and participants (Appendix A); abbreviations and their meanings (Appendix B); a history of factors that influence petroleum exploration and development on the North Slope (Appendix C); and a description of recent technological developments (Appendix D). Appendix E provides the analysis of oil industry data, provided mainly by BP, that was performed for the committee by Aeromap, Inc. Appendixes F and G describe spills of oil and saline water on the North Slope and some of their effects. Appendix H is a signed essay by a North Slope Native on reconciling traditional and Western scientific knowledge. Appendix I, reproduced from an EIS for leasing in the Beaufort Sea, describes the legal framework for oil and gas activities on state lands of the North Slope. Appendix J describes a method for analyzing how economic consequences of long-lasting biotic and physical effects might accumulate. Appendix K provides biographical information about the committee's members.

2

The Human Environment

The harsh climate of Alaska's North Slope shapes and limits the ways that people there live and work. The most notable factor is the extreme cold, which influences the availability of natural resources, restricts transportation and communication, and limits the ways that communities incorporate the amenities of modern western culture. Although there are areas of North America where extreme winter temperatures can be colder than those on the North Slope, the average temperatures there are too low to grow food or timber. Agriculture as a cash-producing activity, and gardens—a traditional supplemental source of food in many other rural areas—are not possible. Similarly, forestry is not possible there.

Arctic tundra is difficult terrain to traverse in summer. The flat coastal regions of the North Slope are poorly drained, so there are thousands of small shallow ponds and boggy ridges that impede transportation in summer. Most of the travel between communities on the North Slope, or between these communities and subsistence areas, is by air, by snow machine in winter when the tundra is frozen, or by water in summer. With the exception of a barge that travels to Barrow once in late summer, transportation between North Slope Native communities and areas off the North Slope is virtually entirely by air.

The NSB's eight main communities (Anaktuvuk Pass, Atqasuk, Barrow, Kaktovik, Nuiqsut, Point Hope, Point Lay, and Wainwright) are not connected to each other by road or to the rest of the state by highway. Table 2-1 provides details of past and current community populations.

Table 2-1 North Slope Population

	Anaktuvuk Pass	Atqasuk	Barrow	Kaktovik	Nuiqsut	Point Hope	Point Lay	Wainwright	Total
1939		78	363	13	89	257	117	341	1,258
1950	66	49	951	46		264	75	227	1,678
1973	134		2,167	144	128	376	31	353	3,333
1980	203	107	2,267	165	208	464	68	405	3,887
1988	264	219	3,335	227	314	591	132	514	5,596
1990	259	216	3,469	224	354	639	139	492	5,792
1993	270	237	3,908	230	418	699	192	584	6,538
1998	314	224	4,641	256	420	805	246	649	7,555

Source: NSB 1999. Anaktuvuk Pass was settled in the late 1940s; Atqasuk and Nuiqsut were abandoned, and then resettled in the 1970s, mainly by former residents of Barrow.

Approximately 70% of NSB residents are Inupiaq Alaska Natives. The remainder of the population is made up of whites (16.8%), Asians (7.2%), other Alaska Natives (2.3%), African Americans and Hispanic people (0.8%), and a sprinkling of other ethnic groups (NSB 1999). The proportion of Inupiaq people is higher in the smaller communities (Anaktuvuk Pass, 92%; Atqasuk, 95%; Kaktovik, 85%; Nuiqsut, 90%; Point Hope, 91%; Point Lay, 92%; Wainwright, 93%) than in Barrow (53%) (NSB 1999). Arctic Village, not part of the North Slope Borough, had 152 people in 2000, of whom 92% were Alaska Native (mainly Gwich'in Indians) (U.S. Census Bureau 2000).

Isolation from major transportation routes and the area's inability to produce construction materials and agricultural products mean that the prices of goods and the cost of transporting them to the North Slope are considerably higher than in the rest of Alaska or the continental United States. In 1998, the cost of a "typical market basket" in Anchorage was $122.19; in Barrow it was $218.03 (NSB 1999) and perhaps double that amount in outlying North Slope villages. Similar proportionate increases occur for vehicles, construction materials, fuel, appliances, tools, and other consumer goods. Because North Slope residents do not have greater per capita incomes than some of their counterparts in the rest of Alaska or in the United States in general (Table 2-2), North Slope residents must accept a lower standard of living, rely to a greater extent on subsistence harvest, or both.

Table 2-2 Per Capita Income for 1999 Compared

Area or Place	Income
Anaktuvuk Pass	$15,283
Atqasuk	$14,732
Barrow	$22,902
Kaktovik	$22,031
Nuiqsut	$14,876
Point Hope	$16,641
Point Lay	$18,003
Wainwright	$16,710
North Slope Total	$20,540
Alaska	$22,660
United States	$21,587

Data from U.S. Bureau of the Census 2000

By comparison, Arctic Village, which is not part of the North Slope Borough and whose residents also rely heavily on subsistence, had a per-capita income of $10,761 in 1999 (U.S. Census Bureau 2000).

The cultural knowledge and practices of North Slope people have been refined over many generations in an environment where one bad decision can lead to an individual death or even starvation of an entire village. The archaeological record shows that there were groups of people whose primary subsistence and economic emphasis was on sea mammals and other groups who relied on caribou from inland areas. Group composition and resource emphasis changed over time, depending on climate, weather, warfare, and shifting political alliances. Although the affiliations and origins of the Inupiat are still unclear, physical anthropological and archaeological data suggest that the North Slope Inupiat have lived along the coastline from Point Hope on the west to the Canadian border on the east roughly since AD 1250 to 1300. The principal form of social organization traditionally revolved around large, extended families ranging from fewer than a dozen to more than 50 people (Burch 1976). The size of a local family was determined by the resource base and the ability of family members to exploit it. Larger families were associated with plentiful game, skilled hunters, or both. Most families lived in clusters of adjacent houses.

Initial contact with Western culture came in the mid-19th century, primarily with the arrival of commercial whalers and Protestant missionaries (Bockstoce 1978, Spencer 1959). Commercial whalers hired North Slope natives as crew members; and Natives later began to captain their own vessels. By 1915, a combination of the introduction of substitutes for baleen and the decline in the bowhead whales population that resulted from overharvesting brought an end to commercial whaling. However, by this time, the cash economy was well-integrated into North Slope culture. Two sources of income rose and fell during this period. Reindeer were introduced in the 1890s by the U.S. Bureau of Education. The reindeer population increased dramatically from the 1,250 originally imported to more than 600,000 animals by the 1930s. By the 1950s, however, overgrazing, increasing predator populations, and losses because animals joined migrating caribou herds had caused the population to decline to fewer than 25,000 (Chance 1966).

Trapping had an even more precipitous trajectory. Although North Slope Natives had traditionally supplemented their incomes by trapping, many more began to do so in the early 1920s when arctic fox pelts rose dramatically in value. In the Great Depression the value of fox pelts dropped, and this source of income dried up (Brower 1942, Sonnenfeld 1956).

Steady-wage jobs were first introduced by the U.S. Navy's early petroleum exploration on the North Slope in the 1940s. Construction of distant early warning radar sites in the 1950s also provided some employment. But throughout the 1950s and 1960s, wage-earning jobs on the North Slope were scarce, and subsistence activities supplied the majority of food for most families.

SUBSISTENCE

Subsistence activities are important to Alaska Native communities of the North Slope. For residents of coastal villages, individual and community identity is tied closely to the procurement and distribution of bowhead whales. Bowhead is the preferred meat and a unique and powerful cultural basis for sharing and community cooperation. Caribou, birds, fish, and plants also are valuable subsistence resources. In inland arctic Alaska—in Arctic Village and Anaktuvuk Pass, for example—caribou are the most important subsistence resource, with lesser use of sheep, moose, and fish. Many people maintain strong cultural and spiritual ties to the resources, so that disruption of subsistence activities affects far more than food supplies.

To understand the subsistence economies of the North Slope, it helps to examine annual subsistence cycles for a coastal and an inland northern Alaskan subsistence system. The following are generic cycles, based on a combination of village and regional data sets (Figure 2-1). For people in most North Alaskan villages, individual participation in the contemporary annual subsistence cycle is both voluntary and variable. Few individuals participate in all

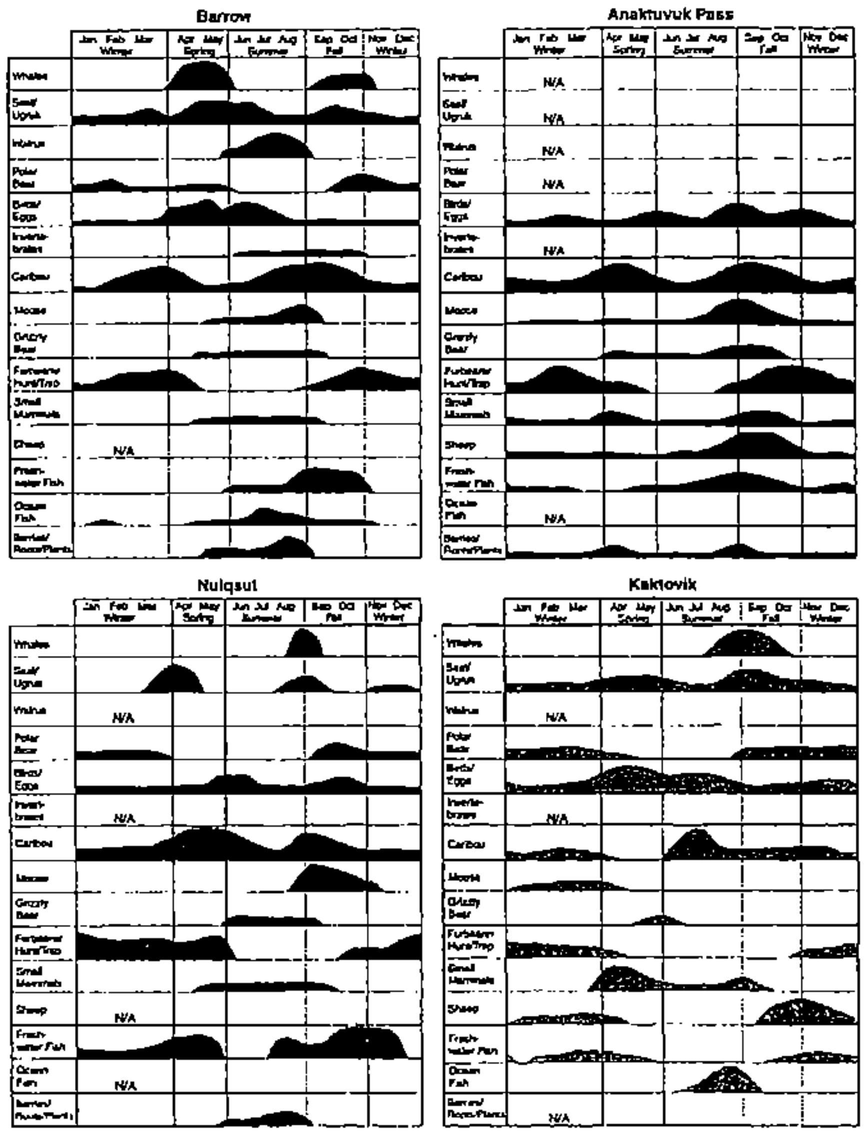


FIGURE 2-1. Seasonal subsistence cycle for four North Slope villages. Thickness of bars indicates relative importance. N/A= food source not available. Source: Galganitis et al. 2001.

activities in every season, but most participate in some. Both the system and the patterns have changed as Alaska Natives have established fixed residential bases and have incorporated new technologies into their subsistence system.

Coastal Northern Alaska

Subsistence harvest patterns for northern Alaska are well described, and qualitative information is available from history references and ethnographic sources (ADF&G 1999; Brower and Opie 1996, 1997; Hall et al. 1985; Harcharek 1995; IAI 1990a,b; Shepro and Maas 1999; S.R. Braund and Associates 1988, 1989, 1993). The following summary is adapted from the work of Galginaitis and colleagues (2001).

Coastal villages can be divided into those for which the bowhead whale is the primary resource, and those that are not geographically positioned to take advantage of spring or fall bowhead whale migrations. For the latter, ringed seal, fish, and caribou are typically the important subsistence resources.

Bowheads are the preferred meat and the most important subsistence resource of coastal villages. The bowhead provides a unique and powerful cultural basis for sharing and community cooperation, and it is the foundation of the sociocultural system (BLM/MMS 1998, Galginaitis et al. 2001). This statement is true for Barrow, Kivalina, Point Hope, Wainwright, Nuiqsut, and Kaktovik.

In pre-contact times North Slope residents expected bowhead whale hunting to provide sufficient fuel and food in four out of five winters (Mason and Gerlach 1995, Simpson 1855, in Bockstoce 1988). In 1852-1853, when few seals and whales were present in the vicinity of Barrow (Bockstoce 1988), people journeyed inland for caribou earlier in the year than usual, and they hunted birds, fished, and ate dogs (Bockstoce 1988). Barrow's subsistence varies less from year to year now than does subsistence in the smaller North Slope Borough villages, for a variety of social and economic reasons (Galginaitis et al. 2001). Quotas, level of effort, weather, ice conditions, and whale migration routes contribute to variable success in the bowhead harvest from village to village, and from year to year.

Subsistence harvest surveys were conducted in Kaktovik in 1985, 1986, and 1992. Caribou harvest surveys were completed in 1987, 1990, and 1991. The caribou harvest over this period was consistent, with a spike 1985, a year in which no bowheads were landed in Kaktovik (Galginaitis et al. 2001). Complete harvest data are available for Nuiqsut for 1985, 1993, and 1994-1995. During these years, Nuiqsut harvested only one whale. In years when the bowhead hunt is unsuccessful, fish and caribou are more important to the overall subsistence economy. In an ideal year, the annual subsistence harvest consists of roughly equal dependence on fish, caribou, moose, and marine mammals in most coastal villages.

Inland Northern Alaska

The committee considered the two inland villages of Anaktuvak Pass and Arctic Village. The subsistence patterns of the inland, predominately Inupiaq, village of Anaktuvuk Pass are not as well studied as are those of the coastal villages (Figure 2-1). Harvest data are available only for 1994-1995 (Brower and Opie 1996), although estimates are available for 1990, 1991, 1992, and 1993 (ADF&G 1999). Those and other historical records (Hall et al. 1985) show that the caribou harvest is the most important subsistence resource in all years (Binford 1978, 2002), but sheep, moose, and fish also are taken. Sharing and exchange with individuals in other communities provide Anaktuvuk Pass residents with access to a wider variety of subsistence resources than they procure directly (Galginaitis et al. 2001, Harcharek 1995, Shepro and Maas 1999). Caribou harvested near Anaktuvuk Pass most commonly come from the Western Arctic and the Teshekpuk Lake herds.

The Arctic Village Gwich'in continue to maintain strong cultural and spiritual ties to the Porcupine Caribou Herd and the Arctic Coastal Plain. The Community Profile Database generated by the Division of Subsistence, Alaska Department of Fish and Game, has no specific harvest information for the Gwich'in community. The limited studies that are available, however, indicate that there is considerable variation in the annual subsistence cycle. The emphasis is on terrestrial mammals, including caribou, moose, and sheep, and on considerable use of furbearers, hare, squirrel, and porcupine. Black and grizzly bears are harvested, but less often than moose or caribou. Ducks, geese, and ptarmigan are seasonally important, as are salmon, grayling, and whitefish. Patterson (1974) suggested that fish are almost as important in terms of quantity and calories as are terrestrial mammals. Caribou, however, are still the most important subsistence resource, integrating people across vast landscapes in northeastern Alaska and Canada.

Subsistence is more than the sum of harvest and resource procurement that has just been used to describe it. Subsistence is ideological, value-driven, and value-laden—an idiom that defines self and community. It is illustrated by specific forms of knowledge about sustainable use of land and resources. It includes a specific suite of behaviors and actions through which wild resources are procured, consumed, and distributed among relatives and neighbors across a wide network of communities.

Therefore, studies of subsistence should be integrated into broader socioeconomic research on contemporary rural life in Alaska, and subsistence activities should be studied in an integrated way that focuses on the everyday reality of life in Alaska Native communities. If this is not done, valuable traditional knowledge will be lost.

NORTH SLOPE HUMAN CULTURES IN THE OIL ERA

The discovery of oil at Prudhoe Bay catalyzed many changes that affected the human environment of the North Slope and that increasingly moved North Slope residents into the mainstream economy. The discovery of oil accelerated political processes for resolving complex issues of land tenure and rights without which investment in, and development of, the oil fields would have been impossible. Of major importance was passage of the Alaska Native Claims Settlement Act in 1971 (see Chapter 4), which established the Arctic Slope Regional Corporation and the village corporations and led to the founding of the North Slope Borough (NSB) in 1972.

The NSB largely overlaps the geographic area of Alaska's North Slope. It is larger than any municipality or county in the United States; it is in fact larger than 39 of the other states. With a land area of 230,036 km^2 (88,817 mi^2) and a human population of 7,555 in 1998, it also has a lower population density—0.033 persons per km^2 (0.085 per mi^2)—than any municipality or county in the United States. The borough's extremely rural nature and the isolation of its small communities are important to consider when assessing the effects of oil and gas activities

(NRC 1994). The population is concentrated in eight communities: Anaktuvuk Pass, Atqasuk, Barrow, Kaktovik, Nuiqsut, Point Hope, Point Lay, and Wainwright. (Deadhorse, at the northern terminus of the James Dalton Highway, is listed as a "place" by the census, but it functions mainly as a support center for the industrial complex surrounding petroleum development. In 1990, its population was 26, of whom 24 were adult males.)

Approximately 70% of NSB residents are Inupiat. The remainder of the population consists of Whites (16.8%), Asians (7.2%), other Alaska Natives (2.3%), African American and Hispanic people (0.8%), and a sprinkling of other ethnic groups (NSB 1999). There are more Inupiat in the smaller communities (Anaktuvuk Pass, 92%; Atqasuk, 95%; Kaktovik, 85%; Nuiqsut, 90%; Point Hope, 91%; Point Lay, 92%; Wainwright, 93%) than in Barrow (53%) (NSB1999). Similarly, 92.1% of Arctic Village's 2000 population of 152 consisted of Alaska Natives (Gwich'in Indians).

The NSB taxes oil and gas facilities and is responsible for education and for an array of other services including water and sewer service, electrical power, health care, housing, transportation infrastructure, and police and fire protection. The borough is the dominant economic force in North Slope communities. Among the main effects of the expansion of services and the capital improvement program were the creation of jobs in direct employment by the borough, the expansion of the educational system, construction projects for the capital improvement program, and the emergence of new businesses as a result of the growing economy. In addition, oil and gas activities have resulted in local energy production for Barrow.

The NSB government, school district, and capital improvement projects; Ilisagvik College; and city, state, and federal governments combined employ 61% of the workforce. Although they are increasingly being employed, North Slope residents are still underrepresented in the oil-field workforce, given that they are approximately 70% of the population. For companies that collected data on residency, of the 7,432 reported individuals who worked on the North Slope in 1999 and who were employed in the oil and gas sector of the economy, only 64 lived in the state's "Northern Region," which consists of Nome and the North Slope and Northwest Arctic boroughs (Alaska Department of Labor and Workforce Development 2001). Part of the explanation of the lower employment proportion is the large percentage of young people, but other factors, such as the need for specially trained, mobile professionals, also contribute. Some North Slope residents obtain oilfield jobs, and then move to Fairbanks or Anchorage. Some later return to their home village, bringing their education and income with them.

3

The Alaska North Slope Environment

The North Slope of Alaska includes about 230,000 km^2 (89,000 mi^2) north of the crest of the Brooks Range, an area slightly larger than Minnesota. It encompasses the drainage basins that empty into the Arctic Ocean and the Chukchi Sea, including the Kongakut River on the east and small drainages east of Point Lay in the west. The land slopes gradually from the crest of the Brooks Range northward to the Arctic Ocean. During the nine-month winter, temperatures can plunge to -50 °C (-58 °F). Annual snowfall averages less than 50 cm (20 in.), but the nearly constant winds produce drifts that are as much as 6 m (20 ft) deep. From November 18 to January 24, the sun never rises above the horizon in Barrow, the northernmost part of the North Slope, although there is a little midday twilight. Conversely, the sun does not set from May 10 until August 2. Annual precipitation ranges from 12 to 20 cm (5-8 in.) along the coast and up to 1 m (40 in.) in the highest elevations of the Brooks Range. Low temperatures reduce evaporation, and permanently frozen soil prevents vertical drainage of water. As a result, extensive areas of the North Slope are covered by thaw lakes, ice-wedge polygons, frost boils, water tracks, bogs, and other features typical of permafrost regions. The patterns created by these features are often difficult to perceive on the ground but are striking from the air. They are particularly well expressed in the Prudhoe Bay region.

To set the stage for the committee's analyses of cumulative effects, we next describe the diverse terrestrial, freshwater, and marine environments of the North Slope.

Terrestrial Environment

Geology

The North Slope is the largest coherent geological province in Alaska. Rocks exposed in the sea cliffs of the Chukchi Sea on the west can be identified in outcrops all the way to the Canadian border on the east. Long ridges of sandstone that continue for many miles in the foothills maintain their east-west orientation and define and expose a giant trough of folded sedimentary rocks, called the Colville Basin or Colville Syncline. The trough extends west to the Chukchi Shelf, where the associated folded structures turn to the northwest and are cut off by vertical faults that mark the eastern border of the Chukchi Basin (Grantz et al. 1994). To the south, that trough is bounded by the overthrust front of the Brooks Range. To the north, it is bounded by, and separated from, the Canada Basin of the Beaufort Sea by a buried ridge of older rocks, a composite structural feature commonly called the Barrow Arch. At Barrow the top of this ridge is only about 700 m (2,300 ft) deep. The arch plunges east to a depth of about 4,000 m

(13,000 ft) in the Prudhoe Bay area and then continues east until it loses its identity as a major structural feature in the Arctic National Wildlife Refuge (Bird and Magoon 1987). The arch extends west into the Chukchi Shelf, and to the north it slopes gently offshore to underlie the Beaufort Shelf. The south flank of the Barrow Arch forms the primary trap for the Prudhoe Bay oil field (Morre et al. 1994). Carbon-rich sedimentary rocks primarily of Mesozoic age are believed to be the source for the oil accumulations that have been found in nearly all of the sedimentary rock units of the Colville Basin.

Permafrost

Permafrost is earth material that stays frozen year-round. On the North Slope it extends to below surface depths of 200-650 m (650-2,000 ft), with the deepest permafrost occurring at Prudhoe Bay. It is insulated from the ground surface by an "active layer," which thaws each summer to a depth of 20 cm (8 in.) in some peats to more than 2 m (80 in.) in some well-drained inland soils. The active layer is subject to continuous natural change, but its disruption by, for example, destruction of the organic insulating mat, or impoundment of surface water, can initiate permafrost thawing and conspicuous surface changes. In extreme cases, called "thermokarst," the differential settlement and loss of strength creates thaw pits, ponds, retreating scarps, or mud flows. To maintain permafrost in its natural frozen condition and to avoid destructive surface settlement, buildings, roads, and other structures must be built on thick gravel foundations and off-site activities must be carefully controlled.

Surficial Geomorphic Features

The North Slope has three distinct regions: the Arctic Coastal Plain, the Arctic Foothills, and the Brooks Range (Gallant et al. 1995). All North Slope oil extraction has occurred on the Arctic Coastal Plain, but there has been some exploration in the foothills.

Arctic Coastal Plain

The coastal plain is generally flat with large oriented thaw lakes and extensive wetlands. The plain is about 150 km (93 mi) wide south of Barrow, and it narrows toward the east. The Prudhoe Bay oil field is within an exceptionally flat portion of the coastal plain (flat thaw lake plains) between the Sagavanirktok and Kuparuk Rivers (Walker and Acevedo 1987). Drainage systems in this portion of the coastal plain are often poorly defined, and much of the runoff occurs in sheet flows, which can shift direction depending on the volume of discharged water.

The Kuparuk oil field is in a somewhat hillier portion of the coastal plain (gently rolling thaw lake plains) (Walker and Acevedo 1987). The hilly aspect of this region is caused in part by large broad-based low hills, or "pingos," created by permafrost and generally 5-20 m (16-65 ft) tall (Walker et al. 1985). Gently rolling plains occur east of the Sagavanirktok River. Those regions have better-defined drainage networks, with more runoff channeled into streams instead of sheet flows.

The dominant geomorphic characteristics of the flat coastal plains are thaw lakes, drained lake basins, polygonal patterned ground, and pingos. Frost boils or nonsorted circles (Washburn 1980) cover large areas of the coastal plain and foothills. Those features typically measure 1-2 m (3.2-6.5 ft) in diameter and are the result of frost heave (Peterson and Krantz 1998). They are highly sensitive to off-road vehicle disturbance, such as that caused by seismic operations.

Thaw lakes are formed by thawing of the frozen ground (Britton 1967, Hopkins 1949) and have a distinct directional orientation attributed to the action of wind (Carson and Hussey 1959, Rex 1961). The lakes grow until they breach other lake basins or stream channels, at which point they empty, leaving drained lake basins (Britton 1967, Peterson and Billings 1980). Ice-wedge polygons dominate the terrain between lake basins. The micro-elevation differences associated with ice-wedge polygons are only a few centimeters (1-2 in.), but soil-moisture differences associated with those small changes in elevation influence the distribution of plants on the landscape.

Pingos are common in drained lake basins, particularly where the water had been deep enough to cause deep thaw zones in the permafrost (Mackay 1979). When lakes drain, those thawed areas are exposed to the weather, and permafrost re-forms. Water is expelled from the freezing soil and an ice core develops, which expands and deforms the soil, eventually forming a hill. Pingos are very stable because of their gravelly parent material and the cold climate.

Rivers west of the Colville meander sluggishly in valleys incised between 15-100 m (50-330 ft); rivers to the east of the Colville are fast flowing, braided, and have extensive delta systems. River systems support a diversity of plant and animal life and can serve as corridors for migrating mammals and birds.

The Beaufort Sea coastline is irregular and contains many small bays, lagoons, spits, beaches, and barrier islands. Extensive mud flats occur in the deltas of the rivers. Most of the coastline is low lying, with only small bluffs less than 3 m (10 ft) high. At Camden Bay, the land rises more steeply from the sea, and the bluffs are up to 8 m (26 ft) high.

Arctic Foothills

The Arctic Foothills is a band, roughly 50-100 km (30-60 mi) wide, of generally smoothly rounded hills between the Arctic Coastal Plain and the Brooks Range. Major drainage systems form broad valleys between the masses of hills. Numerous east-to-west linear bedrock outcrops occur within the foothills, reflecting the orientation of the underlying sedimentary deposits. Most of the hills have gentle slopes with parallel, closely spaced, shallow channels that are unique to permafrost regions (Cantlon 1961). The northern sector of the foothills is smoothly eroded. The hills are covered with late Tertiary to mid-Pleistocene-age glacial till, capped with more recent windblown glacial silt deposits. The southern sector was glaciated more recently (late Pleistocene), and it has many irregular glacial features. The basins between hills have peat deposits and a variety of wetlands (Walker and Walker 1996).

Brooks Range

The Brooks Mountain Range extends almost across the width of Alaska, centered at about 68° north latitude. It is a complexly folded sedimentary mass made up of shale, slate, sandstone, schist, conglomerates, limestone, marble, and granite (BLM 1998). It is incised by north-south river valleys on its north slopes. Maximum elevations reach only about 3,000 m (9,800 ft), but because of the mountains' northern location, they form a barrier to many plants—especially trees—that occur on the south slopes.

Freshwater Environments

Rivers and Streams

Several types of streams are found north of the Brooks Range (Craig and McCart 1975). *Mountain streams*, such as the Colville, Sagavanirktok, Ivishak, and Canning rivers, which originate in the Brooks Range, are the largest river systems that cross the Arctic Coastal Plain. Smaller mountain streams include the Shaviovik and Kavik rivers and most of the streams between the Canning River and the Mackenzie delta in Canada. *Spring streams* are spring-fed tributaries, generally less than 1.5 km (1 mi) long and a few meters wide, that feed the upper reaches of mountain streams. Short, meandering *tundra streams* drain the tundra-covered slopes of the Brooks Range foothills and the coastal plain. They are either tributary to mountain streams or flow directly into the Beaufort Sea. Larger tundra streams include the Ikpikpuk, Meade, Inaru, and Kuparuk rivers.

During winter, river flow ceases except perennial springs (Walker 1983), and ice forms to a thickness of about 1.8 m (6 ft). Smaller streams typically freeze completely; larger streams have water in discontinuous, deep pools. Stream habitat is reduced by 98% during winter (Craig 1989). More than half of the annual stream flow is discharged from Arctic Coastal Plain streams during the 2-to 3-week ice break-up each spring (Sloan 1987).

Lakes and Ponds

Lakes and ponds are among of the most striking landforms of the coastal plain, particularly when viewed from the air. Most lakes in the oil-field region between the Sagavanirtok and Colville rivers are shallow, typically less than 1.8 m (6 ft) deep (Moulton and George 2000). In the Colville delta, site of the Alpine oil-field development, the mean maximum lake depth is 4.5 m (15 ft). Lakes are deeper to the west and south, with a mean maximum depth of more than 9 m (30 ft) in lakes south of Teshekpuk Lake. Many of the lakes are oriented in a north-south direction, a striking feature of the landscape.

Lakes on the coastal plain are typically covered with ice from early in October until early in July. Maximum ice thickness typically reaches 1.8 m (6 ft) by April, but can exceed 2.4 m (8 ft) in some years (Sloan 1987). Shallow ponds become ice-free by mid-to late June, with deeper lakes retaining ice into early July. Teshekpuk Lake, the largest lake on the coastal plain (816 km^2 [315 mi^2]) retains its ice cover into late July or early August.

Because of the dry climate of the North Slope, a substantial amount of surface water evaporates during the short summer (Miller et al. 1980). Much of the snowmelt runoff in the coastal plain during break-up goes to replenish pond and lake water lost to evaporation in summer. In the Barrow area, only about half of the snowmelt becomes runoff; the rest goes into ponds (Miller et al. 1980). In contrast, 85% of the precipitation becomes runoff in the steep drainage basins of the Brooks Range.

Marine Environments

The Chukchi Sea extends from the 200 m (660 ft) isobath of the Arctic Ocean to the Bering Strait (Weingartner 1997). The Alaska Beaufort Sea extends from Point Barrow to the Canadian border (Norton and Weller 1984). The seafloor slopes gently for 50-100 km (30-60 mi) to form the Beaufort Sea shelf, which is among the narrowest of the continental shelves in the circumpolar Arctic. A series of linear shoals landward of the 20 m (66 ft) contour (Reimnitz and Kempema 1984) determines where ice ridges and hummocks form. The larger rivers that discharge into the Beaufort Sea form depositional delta shelves that can extend several kilometers from the shore. Some areas of the coast are directly exposed to the wind, wave, and current action of the open ocean. Other stretches of shore are protected by chains of barrier islands composed of sand and gravel that enclose shallow lagoons.

Ocean Processes

Surface circulation in the Beaufort Sea is dominated by the southern edge of the perpetual clockwise gyre of the Canadian Basin (Selkregg et al. 1975). Most of the year the gyre moves surface water and ice shoreward. The subsurface Beaufort Undercurrent flows in the opposite direction, to the east, over the outer continental shelf (Aagaard 1984). Currents in the shallower waters of the inner Beaufort Sea shelf are primarily wind driven and, thus, can flow either east or west. Because the principal wind direction during the summer ice-free season is from the east, nearshore flow is generally from east to west (Wilson 2001a).

East winds generate west-flowing surface currents that are deflected offshore in response to the Coriolis effect (Niedoroda and Colonell 1990). This offshore deflection of surface waters causes a depression in sea level (negative storm surge), which is partially compensated for by an onshore movement of underlying marine water. Under persistent east winds, bottom marine water can move onshore, where it is forced to the surface. This upwelling of marine water can cause some otherwise brackish and warm areas along the coast to become colder and more saline (Mangarella et al. 1982; Savoie and Wilson 1983, 1986). Under strong and persistent east winds, the negative storm surge causes nearshore water levels to drop as much as 2 m (6.5 ft).

When westerly winds prevail, the Coriolis effect deflects surface waters onshore, causing nearshore water levels to rise. That onshore transport of surface waters is balanced by offshore transport at depth, resulting in regional downwelling along the coast. Those wind-driven marine surges are the principal forces that determine sea level along the coast. Lunar tides along the North Slope are very small, averaging 20-30 cm (8-12 in.) (Norton and Weller 1984, Selkregg et al. 1975, USACE 1998).

The Chukchi Sea receives water flowing northward through the Bering Strait, driven by the half-meter drop in sea level between the Aleutian Basin of the Bering Sea and the Arctic Ocean (Overland and Roach 1987). Pacific waters are an important source of plankton and carbon in the Chukchi and Beaufort seas (Walsh et al. 1989), influencing the distribution and abundance of marine biota and seasonal migrations (Weingartener 1997). The deeper waters (100 m [330 ft]) offshore in the northern Chukchi Sea are a potentially important source of nutrient-rich waters. Waters upwelled from greater depths (250 m [800 ft]) contain nutrients and change the temperature-salinity structure of the northern Chukchi (Weingartner 1997).

Sea Ice

The Beaufort Sea is covered with ice for about 9 months each year. The Chukchi Sea is covered for 8 months of the year. The ice that first forms is weak and easily displaced by wind and waves, often forming pileups and ridges. By late winter, however, land-fast ice about 2 m (6.5 ft) thick extends from the shore to the zone of grounded ice ridges or to a depth of about 15 m (50 ft) (MMS 1987a, Selkregg et al. 1975). Nearshore waters shallower than 2 m (6.5 ft) freeze to the bottom. Seaward of the 2 m isobath, land-fast ice floats and can be displaced during winter into ridges.

The shear zone is a bank of deformed and dynamic ice that extends over waters that are 15-45 m (50-150 ft) deep (Barnes et al. 1984). Here, land-fast ice is sheared by the constantly moving mobile pack ice, resulting in an extensive pressure ridge system of massive ice buildups. Ridge buildups and the accumulation of old ice can be so extensive that large pieces of ice frequently gouge and plow the bottom.

The pack ice zone is seaward of the shear zone. It consists of first-year ice, multi-year ice floes, and ice islands. The pack ice moves from east to west in response to the Beaufort Sea gyre at rates that range from 2.2 km to 7.4 km (1.4 to 4.6 mi) per day (MMS 1987b). Retreat of sea ice begins in June and usually attains its farthest north position (approximately 72° N) by mid-September (NOCD 1986). High rates of biological primary productivity are normally associated with the ice edge (Niebauer 1991) and with areas of upwelling.

By mid-July, the Beaufort Sea is usually ice-free from the shore to the edge of the pack ice, which by late summer retreats from 10 km to 100 km (6 to 60 mi) off shore. River runoff, coupled with the melting of coastal ice, creates brackish (low to moderate salinity) conditions in nearshore areas, particularly near the mouths of rivers. The relatively warm water discharged by rivers and insolation elevate nearshore water temperatures. As summer progresses, this nearshore coastal band of warm, brackish water begins to cool as it mixes with the large sink of cold, arctic marine water. By late summer it is gone, and nearshore waters remain cold and saline until they freeze again in September or October (Wilson 2001a).

Biota

Plants and Vegetation

Arctic vegetation patterns and dynamics are strongly influenced by topography, climate, and soils (Walker et al. 2001a,b; 2002). For the purposes of this report, we divide the vegetation of the North Slope into six general categories (Table 3-1, Figure 3-1). Vegetation patterns in the Brooks Range are complex, but the dominant vegetation on well-drained, wind-blown slopes is generally dry tundra dominated by arctic avens (*Dryas*) (Unit 1). The Arctic Foothills are dominated by moist tussock tundra (Unit 4) with tussock cottongrass, abundant shrubs, and mosses. The Arctic Coastal Plain's wetlands are an intricate mosaic of wet, moist, and aquatic vegetation types. Wet tundra (Unit 6) is dominated by sedges, and mosses. Moderately drained (moist) areas on the coastal plain have either moist nonacidic tundra (Unit 2) with sedges, mosses, and low-growing and creeping (prostrate) shrubs or, on sandy substrates, a dwarf form of moist acidic tussock tundra (Unit 3).

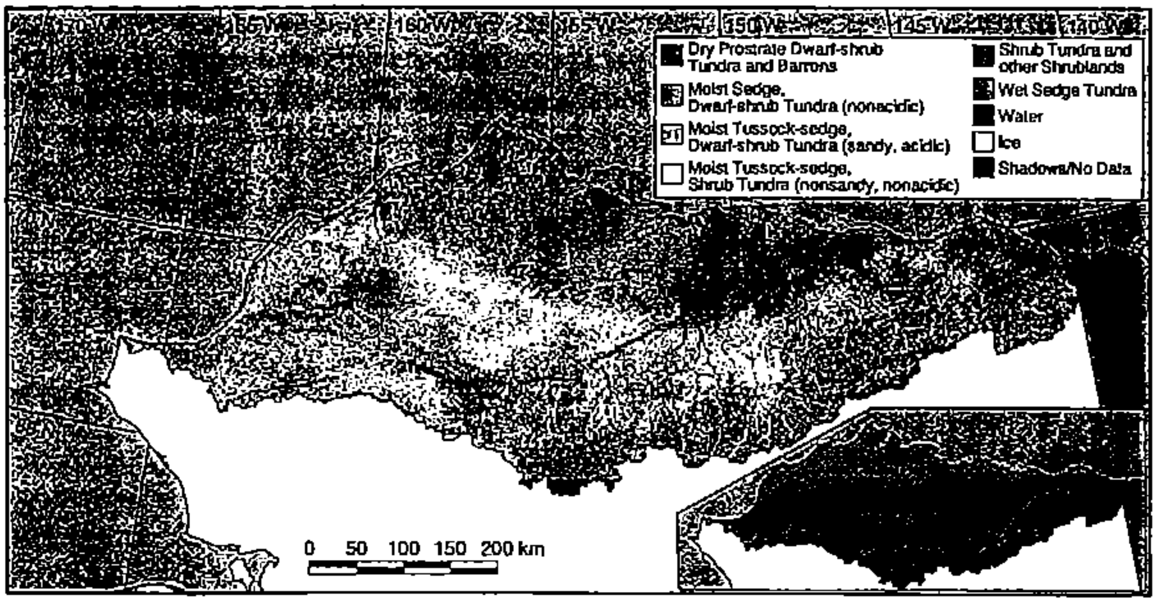


FIGURE 3-1. Major North Slope ecological regions and vegetation types. Source: Alaska Geobotany Center, University of Alaska Fairbanks 2002.

Table 3-1 Area, Percentage Cover of Land-Cover Classes

Unit	Vegetation	Arctic Coastal Plain		Arctic Foothills		Brooks Range		Arctic Slope	
		km²	%	km²	%	km²	%	km²	%
1	Dry prostrate dwarf-shrub tundra and barrens	1,778	3.58	1,493	1.56	13,566	24.31	16,887	8.37
2	Moist sedge, dwarf-shrub tundra (nonacidic)	12,088	24.32	20,340	21.29	11,248	20.16	43,676	21.72
3	Moist tussock-sedge, dwarf-shrub tundra (sandy, acidic)	4,958	9.97	2,540	2.66	0	0.00	7,499	3.73
4	Moist tussock-sedge, shrub tundra (nonsandy, acidic)	5,693	11.45	38,728	40.53	11,101	19.90	55,522	27.61
5	Shrub tundra and other shrublands	1,969	3.96	26,117	27.33	9,252	16.58	37,338	18.57
6	Wet sedge tundra	13,303	26.76	3,702	3.87	1,020	1.83	18,025	8.97
7	Water	9,874	19.86	2,369	2.48	535	0.96	12,778	6.36
8	Ice	17	0.03	97	0.10	1,283	2.30	1,397	0.69
9	Shadows	0	0.00	164	0.17	6,881	12.33	7,045	3.50
10	No data	31	0.06	6	0.01	909	1.63	946	0.47
	Total	49,711	100.00	95,556	100.00	55,795	100.00	201,062	100.00

Source: Modified from Muller et al. (1999).

Climate varies greatly with distance from the coast. A narrow band along the Beaufort Sea coast is influenced by the ice pack and by cold ocean waters; mean July temperatures are about 4-7 °C (39-45 °F). Shrubs near the coast are low growing or prostrate. Local flora near the coast consists of fewer than 150 vascular plant species. Most of the coastal plain is somewhat warmer in summer, with mean July temperatures of 7-9 °C (45-48 °F); the flora includes 150-250 plant species. Shrub heights in open tundra reach about 40 cm (16 in.) near the southern edge of the coastal plain. In the foothills, mean July temperatures are about 9-12 °C (48-54 °F). Tussock tundra covers vast areas, and the local flora exceeds 400 species. In the warmer areas of the foothills, shrub tundra occurs with shrubs that are taller than 40 cm (16 in.). Willows taller than 2 m (6.5 ft) and alders grow along the rivers in the foothills. Some cottonwoods grow in the warmest oases and at some springs along the rivers.

Soil pH varies considerably across northern Alaska, and it is an important factor in controlling patterns of vegetation and many other ecosystem processes. It also affects the distribution of wildlife. Much of the Arctic Foothills and a large sandy area west of the Colville River on the coastal plain have acidic, nutrient-poor soils that support tussock-tundra vegetation types dominated by tussock cottongrass, dwarf shrubs, and mosses (Units 3 and 4). Those vegetation types generally have few plant species that have low nutrient concentrations and high concentrations of anti-herbivore protective chemical compounds. In contrast, moist nonacidic tundra (Unit 2) occurs in areas with mineral-rich soils, such as loess (windblown glacial silt) deposits, alluvial floodplains, and late-Pleistocene-age glacial surfaces. These areas have relatively high soil pH; shallow organic layers; relatively warm, deeply thawed soils; more plant species; and plants with fewer anti-herbivore chemical compounds than those found in areas of acidic tundra (Walker et al. 1998). The importance of moist nonacidic tundra to wildlife has not been studied specifically, but the combination of the factors described above and the fact that all of northern Alaska's caribou herds calve in areas dominated by nonacidic tundra suggests that it is important wildlife habitat (Walker et al. 2001b).

Tundra Ecosystems

Tundra ecosystem productivity is limited by the short Arctic growing season, by low temperatures, and because plant growth cannot begin in spring until thawing of the active layer releases nutrients and water. Much of the initial growth of tundra plants in spring and early summer is supported by stored nutrients, not by current uptake (Chapin and Shaver 1985, 1988; Chapin et al. 1980, 1986). An adequate supply of nutrients, especially nitrogen and phosphorus, is required at the start of the growing season when growth is most rapid. Nutrients stored in the plants' tissues are available when most needed and are replenished later in the growing season when the soil is thawed more deeply and when aboveground growth has greatly diminished. Nitrogen-fixing species, such as legumes, alder species, and several species of moss and lichen (Chapin and Bledsoe 1992), rarely dominate tundra vegetation, but they control the input of nitrogen during vegetation succession. Nutrient storage reduces annual variations in community productivity because growth rates are strongly influenced by average conditions over several years rather than by those of the current year.

Plant species affect the quality of the soil substrate for microbes, the primary decomposers of litter. In general, deciduous leaf litter decomposes faster than does evergreen leaf litter. Mosses, lichens, roots, and woody stems decompose even more slowly (Clymo and Hayward 1982, Nadelhoffer et al. 1992). Plants also influence microbial activity by altering soil temperature, moisture, pH, and redox potential. Mosses promote low soil temperatures and permafrost development by conducting heat under cool, moist conditions and by insulating soils under warm, dry conditions (Oechel and Van Cleve 1986).

Plant species influence biogeochemistry by affecting rates of herbivory. In general, browsers and grazers prefer deciduous and graminoid (grasses and sedges) species to evergreens. If plants have a low tolerance for herbivory because of their low nutrient availability or low regrowth potential, sustained herbivory can shift the community composition toward less palatable species, thereby reducing nutrient recycling rates (Pastor et al. 1988).

The most important consumers of living and dead plant tissues in terrestrial Arctic tundra are mammals (hoofed mammals, rodents), birds (geese, ptarmigan), arthropods (insects, mites, tardigrades), and nematodes. Vertebrate herbivores of the arctic tundra all have varied diets, but the mixture of graminoids and woody species normally eaten varies among species. Few species feed heavily on lichens, other than caribou, which depend on lichens for winter feeding.

Arthropods are abundant in tundra ecosystems, but the diets of most species are not well known. About half of the insect fauna in the Arctic consists of flies (Danks 1990). The larvae of some of these species eat living plant tissues, but most of them live in the soil or mud in tundra ponds and feed on dead plant material. Other consumers of plant material are springtails (*Collembola*), moths (*Lepidoptera*), and beetles (*Coleoptera*), but their relative importance in tundra ecosystems is unknown. Water bears (tardigrades) and nematodes are abundant in tundra soils, but most species are undescribed and their feeding habits are unknown. Earthworms are unaccountably absent from North American tundra although they are found in Eurasian tundra (Chernov 1995). Lapland longspurs and snow buntings and several species of plovers and sandpipers are important avian predators of tundra arthropods.

Herbivores are the food resource for an array of carnivores that spend part or all of the year on the North Slope. The mammalian carnivores of the Arctic Coastal Plain—wolf, arctic fox, and ermine—are active year-round. Omnivorous mammals—red fox, wolverine, and brown bear—eat plant and animal matter and are important scavengers. Except for the bears, which hibernate during winter, all are active throughout the year.

Raptors in the Arctic Coastal Plain (snowy and short-eared owls and northern harriers) are generally restricted to ground-nesting species because of the small number of cliff nest sites in this region (Ritchie and Wildman 2000; Swem, unpublished material). Abundances of these species are low and highly variable (Batzli et al. 1980; Swem, unpublished material), and they fluctuate in synchrony with the lemming cycle (Batzli et al. 1980). Peregrine falcons, gyrfalcons, golden eagles, and rough-legged hawks are concentrated in the foothills of the Brooks Range, where they nest on cliffs, shale, and soil cut-banks adjacent to rivers and some lakes (Ritchie and Wildman 2000, Wildman and Ritchie 2000). Their abundances have been stable or increasing (Wildman and Ritchie 2000).

Aquatic Ecosystems

Freshwater Ecosystems

Much of the Arctic Coastal Plain is covered by shallow lakes and ponds. Those deeper than 1.8 m (6 ft) do not freeze to the bottom during winter and typically harbor fish. Shallower lakes that freeze completely during winter do not have fish but they have high densities of benthic and planktonic invertebrates. Live and decaying vegetation in those lakes is consumed primarily by larvae of arthropods, principally craneflies and midges. Those insects constitute the primary food supply for the thousands of shorebirds that breed on the wet tundra during the brief summer.

Ponds that contain emergent sedges are essential brood-rearing habitats for most ducks (Bergman et al. 1977), and islands in those ponds are preferred nesting sites for some waterfowl. Consequently, bird densities tend to be high in the mosaic of wet meadow, ponds, and drained lake basins near the coast (Cotter and Andres 2000, Derksen et al. 1981), and in riparian areas (FWS 1986). The Colville River delta also supports high densities of waterfowl and shorebirds. Lakes northeast of Teshekpuk Lake are important molting areas for brant and white-fronted geese (King 1970).

Most bird species that breed on Alaska's North Slope nest in tundra habitats, associated wetlands, or adjacent marine lagoons. More than 130 species have been recorded on the coastal plain of the Arctic National Wildlife Refuge (FWS 1986). Dominant groups, both in number of species and in abundance, are waterfowl—ducks, geese, and swans—and shorebirds. Loons are of interest because their populations are generally declining elsewhere in Alaska (Groves et al. 1996). Yellow-billed loons and eiders are of special concern because their range within the United States is concentrated in northern Alaska, where they occur in low densities. Some other species are of special concern because they congregate in large numbers to molt in coastal lagoons and wetlands.

Marine Ecosystems

The Arctic Ocean has very low biological productivity despite supporting a specialized biotic community. In winter, when marine nutrient concentrations are at their annual peak, there is little or no sunlight to drive photosynthesis. In summer, when there is ample sunlight, nutrient concentrations are low because the lack of mixing results in a stratified water column. The southern Chukchi Sea has high primary production, some of which is exported to the northern Chukchi Sea and the Arctic Ocean (Walsh et al. 1989). The ecology of the northern Chukchi Sea is poorly understood, but the presence of the ice edge and upwelling suggests high biological production (Weingartner 1997). In general, sea ice plays a complex ecological role through spring lead zones, polynyas, and other seasonal changes in structure.

Inorganic nutrient concentrations in the surface waters of the Beaufort Sea are typically lowest during summer, when nitrate and phosphate are almost undetectable (Horner 1981) because of phytoplankton uptake and water column stratification. During winter, stratification slows and increased vertical mixing replenishes surface-water nutrients. Strong upwelling in some regions of the Beaufort Sea supplies deep, nutrient-rich ocean water to nearshore areas. River discharge is another source of nutrients, especially nitrates and silicates, during the spring thaw when river flows are at their peak (Wilson 2001b).

Primary production in the Arctic Ocean is carried out by three groups of organisms: phytoplankton, epontic ice algae (algae that grow on the under surface of ice), and attached benthic macroalgae. Benthic microalgae, which consist primarily of diatoms, do not contribute significantly to primary production in the Arctic Ocean (Dunton 1984, Horner and Schrader 1982).

More than 100 phytoplankton species, mostly diatoms, dinoflagellates, and flagellates, have been identified from the Beaufort Sea (MMS 1987b). Phytoplankton are generally most abundant in nearshore waters shallower than 5 m (16 ft) (Horner 1984, Schell et al. 1982). Except for isolated areas near Barrow and Barter Island, there are none of the dramatic plankton blooms in the Beaufort Sea that are typical of more temperate waters (Horner 1984). Rather, there is a gradual, moderate increase in phytoplankton biomass that begins in late spring with ice break-up, peaks in mid-summer when sunlight is most intense, and decreases in late summer when the days shorten.

Because of the low primary production, zooplankton communities are characterized by low abundance, low diversity, and slow growth rates (Cooney 1988). Herbivorous copepods dominate the Beaufort Sea zooplankton (Johnson 1956, Richardson 1986); amphipods, mysids, euphausiids, ostracods, decapods, and jellyfish (Wilson 2001a) also are present.

The abundance and diversity of infauna—invertebrates in the substrate—tends to be low during summer in nearshore areas shallower than 2 m (6.5 ft) because that zone is covered by land-fast ice in winter. Sedentary infauna are slow to recolonize the disturbed benthic environment. Biomass and diversity increase with depth, except in the shear zone—15-25 m (50-80 ft)—which is subject to intensive ice gouging that presumably destroys substrate-inhabiting organisms. Seaward of 40 m (130 ft), ice no longer disturbs the benthos (Carey 1978). Infaunal species include foraminifera, polychaetes, nematodes, amphipods, isopods, bivalves, and priapulids.

Organisms that live on the surface (epifauna) are more motile and readily dispersed by currents. Some groups, such as mysids, migrate on and offshore seasonally (Alexander et al. 1974, Griffiths and Dillinger 1981). Epifaunal organisms are an important food source for several bird and fish species that inhabit coastal waters during summer (Craig et al. 1984).

Epontic communities consist of microorganisms, mostly diatoms, that live on or in the under-surface of sea ice (Horner and Alexander 1972). Light is the major factor that controls the distribution, development, and abundance of those assemblages (Dunton 1984, Horner and

Schrader 1982). Epontic algae are estimated to contribute 5% of the annual total primary production in nearshore Beaufort Sea coastal waters (Schell and Horner 1981). Ice algae assemblages serve as a food source for a variety of invertebrates, including copepods and amphipods, particularly during early spring when other sources of food are in short supply (Wilson 2001a).

Much of the Beaufort Sea floor is covered by silt and sand (Barnes and Reimnitz 1974), but there is an isolated area of rock- and cobble-littered seafloor, called the Boulder Patch, several kilometers offshore from the mouth of the Sagavanirktok River in Stefansson Sound (Dunton and Schonberg 1981, Dunton et al. 1982, Martin and Gallaway 1994). The Boulder Patch supports a community of several species of large red and brown algae and a diverse assortment of invertebrates representing every major phylum (Dunton and Schonberg 2000, Dunton et al. 1982, Martin and Gallaway 1994).

The most conspicuous member of the community is the kelp, *Laminaria solidungula*. Beneath the overstory is another seaweed assembly dominated by several species of red algae. Kelp produce 50-56 % of the carbon available to Boulder Patch consumers. Growth of kelp is both energy- and nitrogen-limited because those two resources are not available in sufficient quantities simultaneously (Dunton 1984). Sponges and cnidarians are the most abundant and conspicuous invertebrates in the Boulder Patch community. Bryozoans, mollusks, and tunicates are common on rocks and attached to other biota. A species of chiton constitutes a large percentage of molluscan biomass and is one of the few species that graze on kelp.

The abundance and diversity of epifauna in nearshore waters that are shallower than 2 m (6.5 ft) in summer is similar to the abundance and diversity in deeper surrounding zones because mobile invertebrates can rapidly recolonize shallows once the ice lifts off the seafloor and the ice cover recedes. Some species find winter habitat in deep holes within the land-fast zone. Mysids and amphipods dominate the nearshore epifaunal community (Griffiths and Dillinger 1981, Moulton et al. 1986). Epifauna from 33 trawls done in the northern Chukchi and western Beaufort Seas in 1977 were described by Frost and Lowry (1983), who identified 238 invertebrate species or species groups and two major community types.

The mobility of epifauna, either active or via passive transport, can be critical in maintaining a robust food web. Griffiths and Dillinger (1981) estimated that feeding by birds and fish within Simpson Lagoon would be sufficient to deplete the basin of mysids rapidly were it not for a substantial and continual immigration of mysids from offshore coastal waters.

Seventy-two species of fish have been identified in freshwater and marine habitats on and around the North Slope, although only 29 of them are common. Some 17 species, of which arctic cisco (*Coregonus autumnalis*) and broad whitefish (*C. nasusare*) are of highest value, are important for the subsistence harvest.

Several bird species use arctic marine environments for food, including gulls, loons, and the sea-duck species. The coastal barrier island and lagoon systems are important molting and staging areas for waterfowl. Most waterfowl species depend more on freshwater than saltwater for their habitat and food requirements. The Beaufort Sea is also important habitat for whales, seals, and polar bears.

4

History of Oil and Gas Activities

The Inupiat used oil and gas seeps for fuel in Arctic Alaska long before the first whalers or other outsiders ventured to the North Slope. Active industry exploration began in the late 1950s when federal geological studies supported the premise that a significant reserve potential existed, and the land was released for industry leasing.

By 2001, oil development on Alaska's North Slope consisted of 19 producing fields and a network of roads, pipelines, and power lines that connect drill sites, production facilities, support facilities, and transportation hubs. Most of those facilities were in place before 1988, by which time the rate of growth had declined because of the full development of the large Prudhoe Bay and Kuparuk oil fields and as a result of changes in technology.

Highlights of the North Slope's oil and gas exploration and development history are summarized in Table 4-1. Appendix C is a more thorough description.

Table 4-1 Oil Exploration and Development on the North Slope

Before recorded history	Visible oil seepages used by Native inhabitants of the North Slope
1882	U.S. government representatives hear of oil seepages while traveling in the area
1886	First non-Natives see seepages at Cape Simpson
1909	First description of Cape Simpson deposits published
1914	First oil-related claim staked
1921	Additional claims staked by individuals and industry
1921	Large deposits of oil discovered in Oklahoma and Texas; industry loses interest in the remote Arctic
1922	First industry-sponsored geological investigation of North Slope oil potential
1923	Naval Petroleum Reserve No. 4 (PET-4) established
1923-1926	First analysis of National Petroleum Reserve-4 potential
1943	Territory of Alaska Bureau of Mines sends field party to the North Slope to investigate oil and gas seepages
1944	Start of PET-4 petroleum exploration program. PET-4 headquarters established at Barrow Land north of the drainage divide of the Brooks Range withdrawn from public entry by the secretary of the interior, Public Land Order 82

Table 4-1 (continued)

1945-1952	Numerous geophysical studies conducted across PET-4 find oil and gas
1947	Office of Naval Research establishes Arctic Research Laboratory
1953	National Petroleum Reserve-4 unexpectedly recessed
1953-1968	Federal geologic field studies continue in National Petroleum Reserve-4; several major oil companies begin exploration
1957	Oil discovered in Cook Inlet (south-central Alaska)
1958	Public Land Order 82 modified; federal leasing begins on the North Slope; first industry-sponsored geological field programs; Alaska Statehood Act passed
1962	First industry-sponsored seismic program
1963-1967	First industry exploration well drilled on the North Slope; 11 unsuccessful wells drilled; industry interest in the North Slope wanes
1964	First State of Alaska lease sale on the North Slope
1965	Area that eventually includes Prudhoe Bay leased
1967	Initial exploratory drilling at site that would become Prudhoe Bay field
1968	ARCO announces the discovery of Prudhoe Bay oil field, the largest in North America
1969	Kuparuk, West Sak, and Milne Point fields discovered; lease sales suspended on the North Slope for the next 10 years because secretary of the interior imposes freezes due to Native Claims
1970	Alaska Environmental Policy Act passed
1971	Alaska Native Claims Settlement Act passed
1974-1976	Federally sponsored exploration along the Barrow Arch
1976	National Petroleum Reserve-4 is transferred from the Navy to the Department of the Interior and renamed the National Petroleum Reserve in Alaska; sale of crude oil from the Petroleum Reserves 1, 2, and 3 authorized
1977	Trans-Alaska Pipeline system operational
1979	Initial leasing of portions of state and federal outer continental shelf (OCS) waters of the Beaufort Sea
1980	Alaska National Interests Land Conservation Act passed
1981	First OCS exploration well drilled
1982	Initial leasing of portions of the National Petroleum Reserve-Alaska
1984-1985	Seismic exploration of the Arctic National Wildlife Refuge 1002 Area conducted
1985	First industry exploration well drilled in the National Petroleum Reserve-Alaska
1986	Arctic Slope Regional Corporation well drilled within the coastal plain of the Arctic National Wildlife Refuge
Various times	Initial leasing of portions of Arctic Slope Regional Corporation lands
Early 1990s	Last of the National Petroleum Reserve-Alaska leases from the initial leasing program are relinquished
1994	Discovery of Alpine field
2001	Northstar field begins production Development of Liberty field suspended

Maps depicting active leases (Figure 4-1) and exploration wells (Figure 4-2) indicate where industry interest, intensity of exploration, and infrastructure have been concentrated, but both leasing and exploration have covered additional areas not mapped. During the 1990s, interest expanded from the Prudhoe Bay area to the west into the National Petroleum Reserve-Alaska and offshore. More recently, leasing has moved south into the foothills of the Brooks Range and in the Point Thompson area.

The Prudhoe Bay oil field was established in 1968 with a small airstrip, a camp, and a peat road to an exploration well (Figure 4-3). The only permanent structures in the area before those were the distant early warning line facilities at Point Strokerson and Oliktok, and a few sod houses built by the Inupiat. By 1970, after the confirmation of the Prudhoe Bay oil field, airstrips, roads, and other gravel infrastructure was built or expanded to connect distribution centers to camp facilities and remote drilling sites. The growth of this development is shown in Figures 4-4, 4-5, and 4-6. An important milestone was the completion of the North Slope Haul Road, eventually called the James Dalton Highway, which formed the work path for constructing the Trans Alaska Pipeline and links Prudhoe Bay to the outside world.

Box 4-1 The Haul Road

The Haul Road (James Dalton Highway) runs 667 km (415 mi) from Livengood, which is near Fairbanks, to Deadhorse, Alaska. The sole overland route to the North Slope, the northern portion of the Haul Road was closed to the public until 1995, when the highway was opened to public access as far as the security gate at the Prudhoe Bay oil field. Annual truck traffic has increased substantially since the early 1990s. In 1996, 45,000 trucks used the road (National Petroleum Reserve-Alaska FEIS III.C-55).

To the west, the Kuparuk oil-field road network began to expand in 1978. The average length of roads added each year during expansion (26.1 km [16.2 mi]) (Walker et al. 1986a) was similar to that at Prudhoe Bay (22.5 km [14 mi]) (Walker et al. 1986a), although gravel pads at Kuparuk were smaller and spaced farther apart than were those at Prudhoe Bay.

After 1977, gravel mining in upland tundra sites replaced floodplain scraping as the source of roadbed material. Those deeper mines reduced the area of disruption caused by mining, and the effects on diverse riparian systems were reduced as a result.

ANATOMY AND OPERATION OF NORTH SLOPE OIL FIELDS

Oil-field operations on the North Slope involve four distinct but closely related phases: leasing, exploration, development, and production and transportation. We present these sequentially for clarity, but they can occur out of sequence. For example, seismic exploration can occur before leasing or during the development phase. Each phase has unique elements and some that are shared with other phases. The result is the complex diagrammed in Figure 4-7.

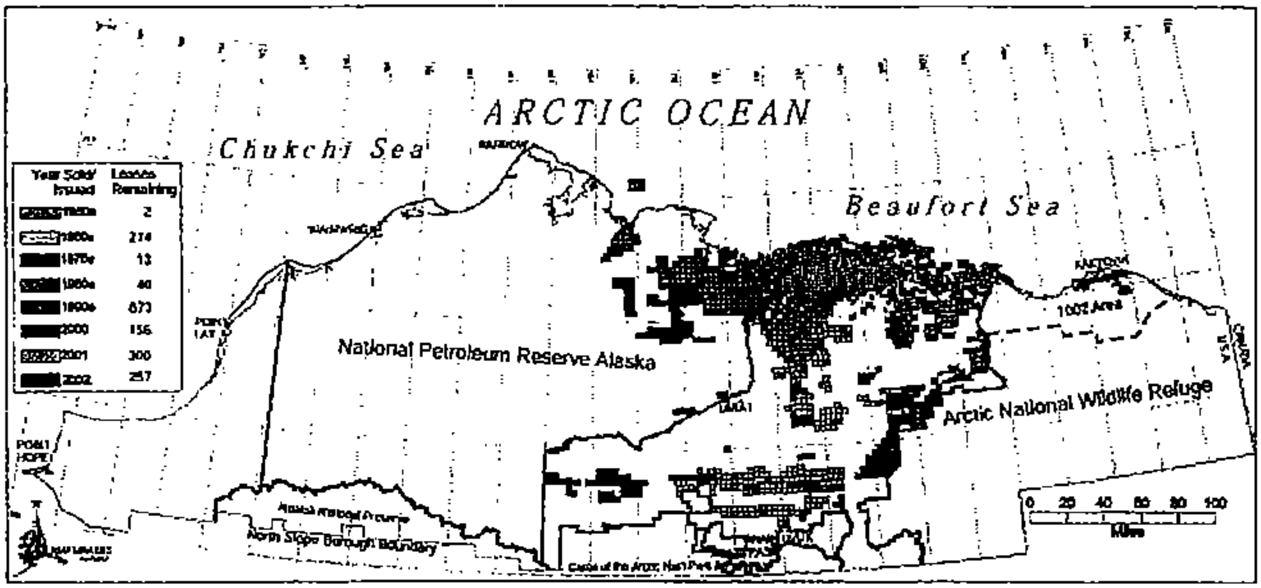


FIGURE 4-1. Time of acquisition of current leased lands on the North Slope of Alaska. The leases acquired during the 1900s are shown by decade and those since 2000 by year. The age of the leases indicates the recent shift in exploration interest to the south and west. Earlier leases that have been relinquished are not shown. Drawing by Mapmakers Alaska 2002.

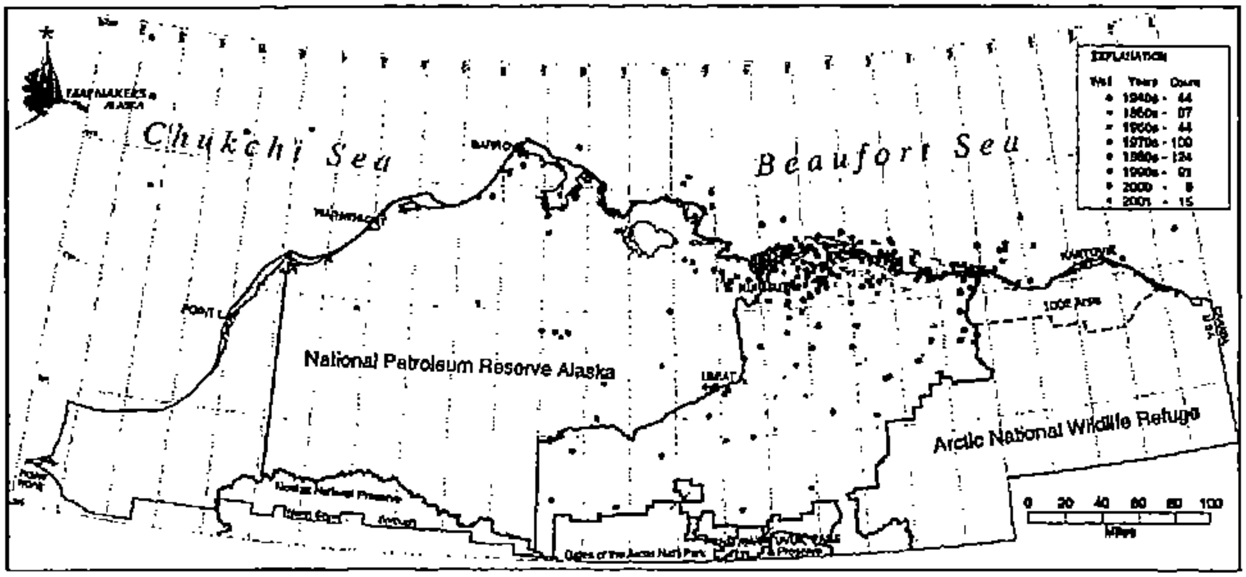


FIGURE 4-2. Location and drilling date of exploration wells on the North Slope of Alaska. Wells drilled during the 1900s are grouped by decade and those since 2000 are depicted by year. Note the heavy concentration of exploration drilling along the Barrow Arch, between the National Petroleum Reserve-Alaska and the Arctic National Wildlife Refuge. Drawing by Mapmakers Alaska 2002.

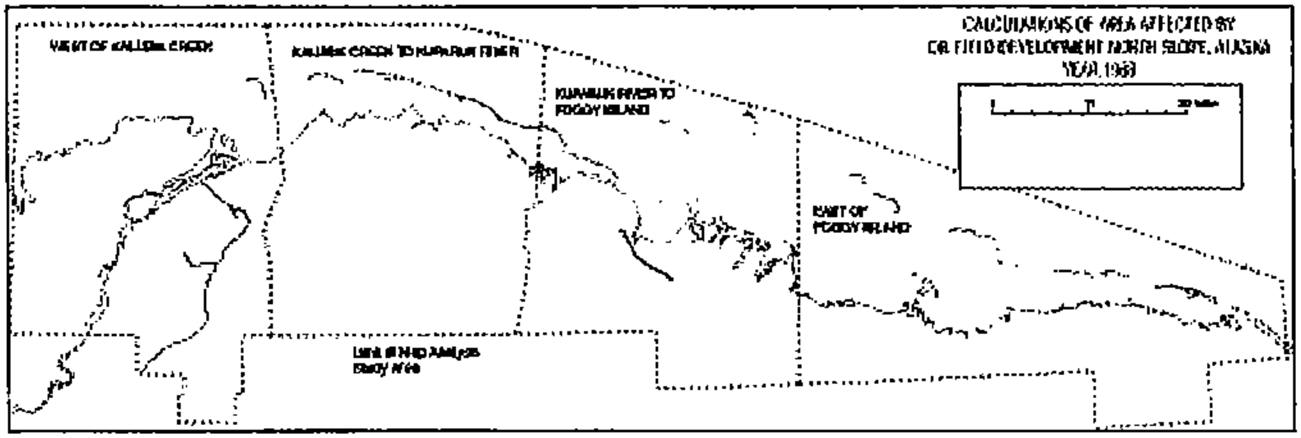


FIGURE 4-3. Road network for oil-field development, 1968. Area calculations were obtained from topographic maps and historical aerial photography provided by BP Exploration (Alaska) Inc. Funded by the National Academies. Interpretation and calculation were done by Ken Ambrosius, Aeromap USA 2002.

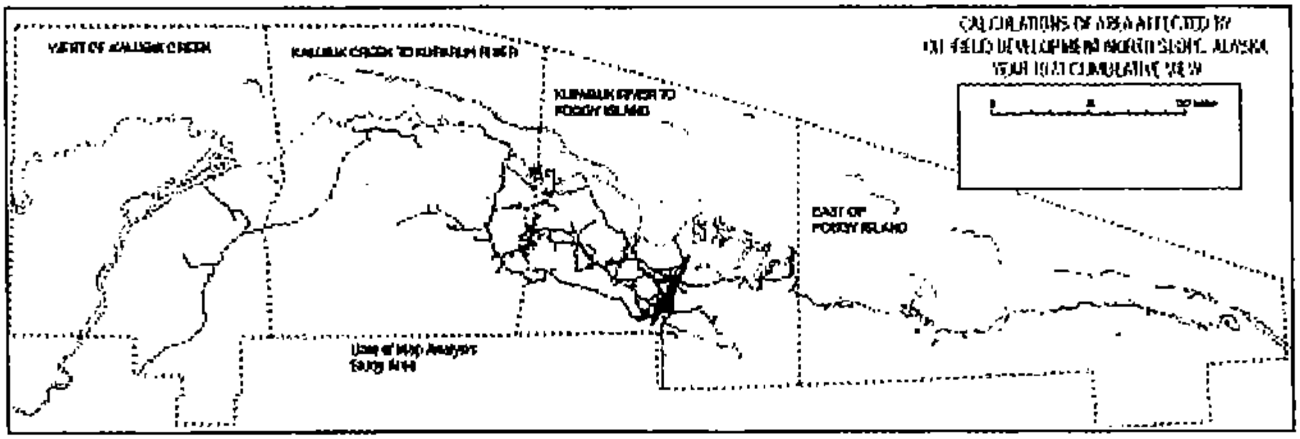


FIGURE 4-4. Road network for oil-field development, 1973, cumulative view. Area calculations were obtained from topographic maps and historical aerial photography provided by BP Exploration (Alaska) Inc. Funded by the National Academies. Interpretation and calculation were done by Ken Ambrosius, Aeromap USA 2002.

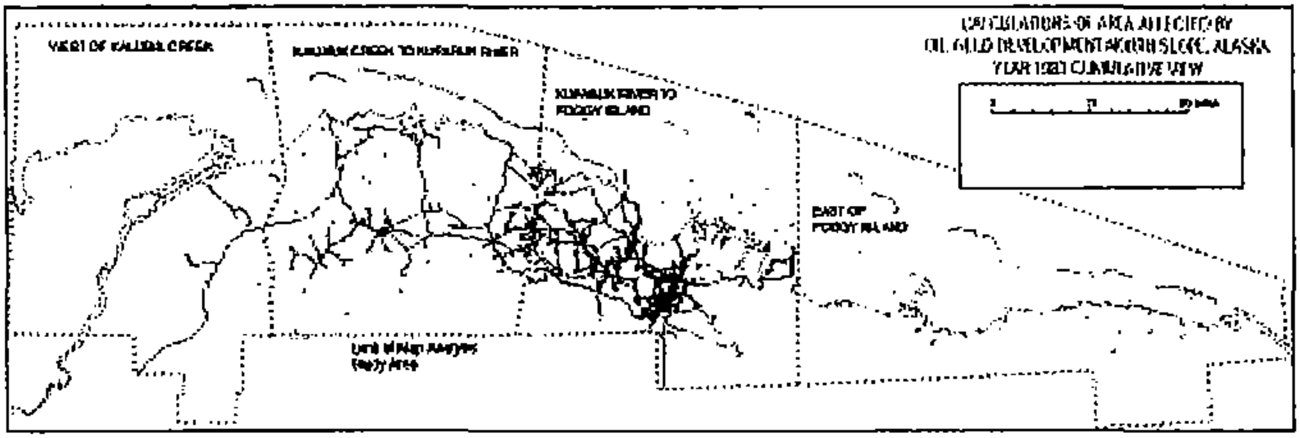


FIGURE 4-5. Road network for oil-field development, 1983, cumulative view. Area calculations were obtained from topographic maps and historical aerial photography provided by BP Exploration (Alaska) Inc. Funded by the National Academies. Interpretation and calculation were done by Ken Ambrosius, Aeromap USA 2002.

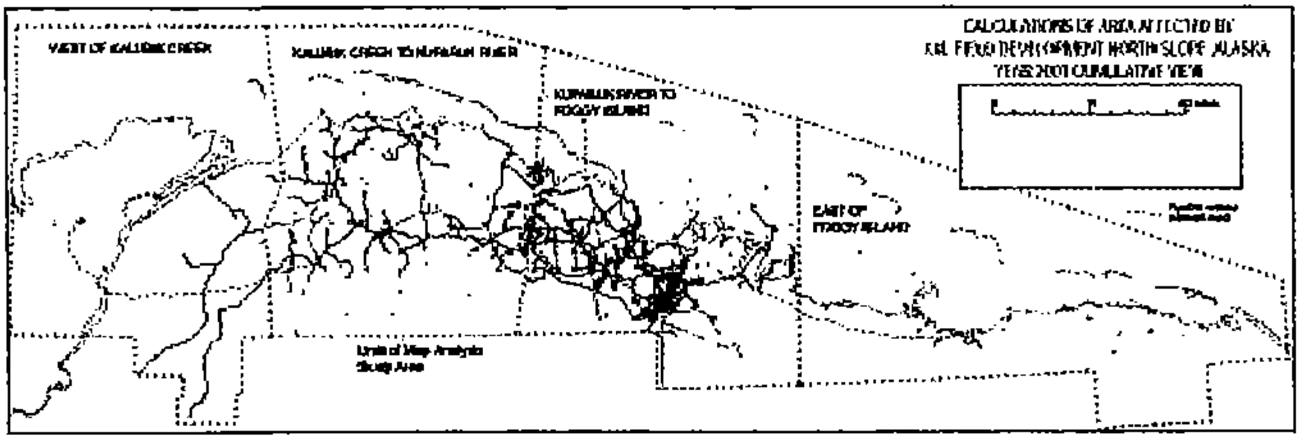


FIGURE 4-6. Road network for oil-field development, 2001, cumulative view. Area calculations were obtained from topographic maps and historical aerial photography provided by BP Exploration (Alaska) Inc. Funded by the National Academies. Interpretation and calculation were done by Ken Ambrosius, Aeromap USA 2002.

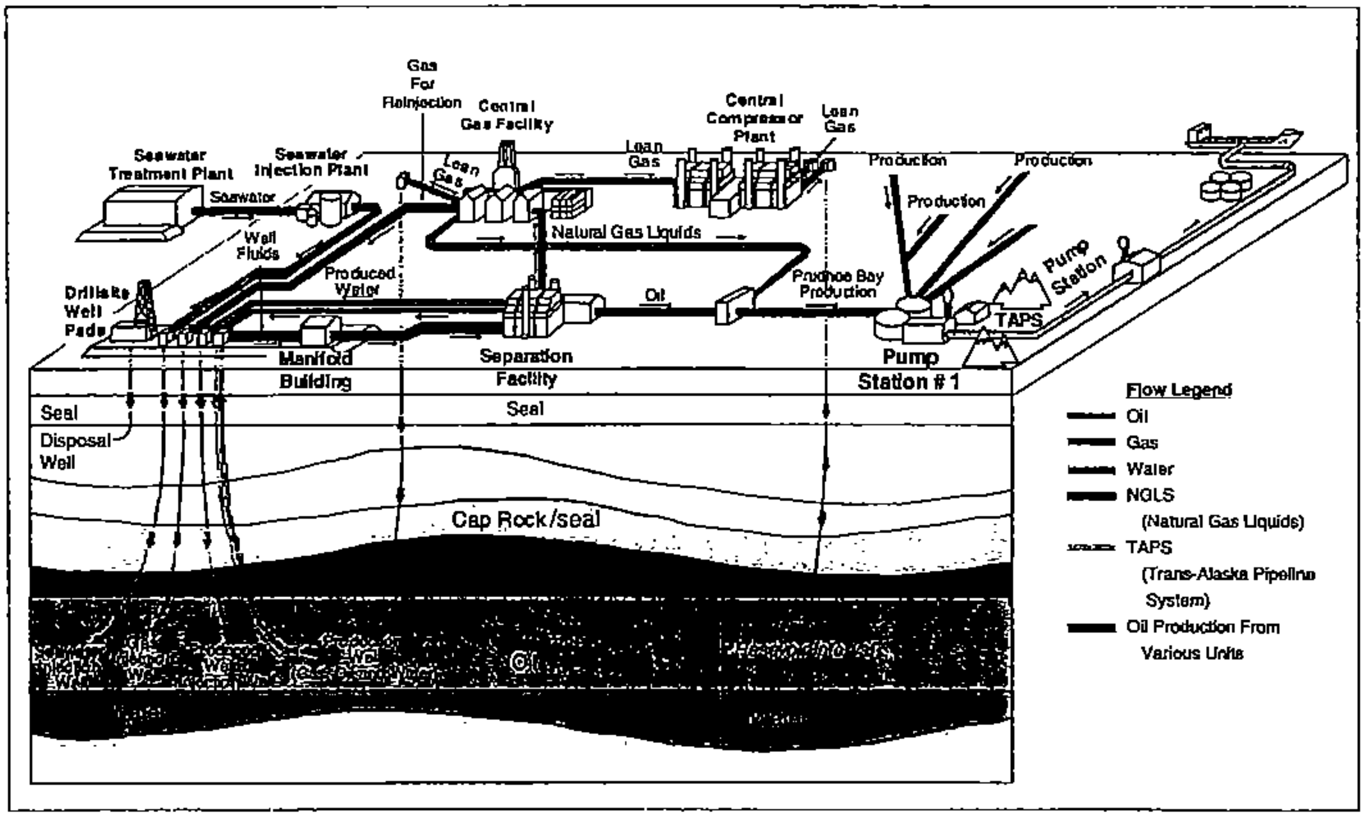


FIGURE 4-7. Schematic diagram of North Slope oil-field operations. Source: Modified from Alaska Department of Natural Resources, Division of Oil and Gas, unpublished material 1996.

Leasing

Mineral rights, or the right to extract resources from beneath the ground, are sometimes, but not always, attached to the ownership of the surface area. Either way, clear title to mineral rights must be obtained through purchase or lease.[1]

When rights are owned by a public institution, such as a state or the federal government, the leasing process is public, and it usually is preceded by announcements of lease sales and by competitive bidding. Information concerning leasing, or even potential leasing and development, usually affects various interested parties.

Exploration

Exploration, the most widely dispersed activity, leads to development and production when economically developable quantities of oil or gas are discovered. Historically, such quantities have been found 10-20% of the time in "frontier" areas and as much as 60-70% of the time in mature areas near established fields.

Seismic Exploration

Unless a well is in a previously tapped reservoir, one or more seismic surveys usually are conducted before drilling begins. An initial summer survey of a proposed area is followed by winter surveys that use vibrating equipment and receivers placed on the tundra along a rectilinear grid. The vibrators generate sound waves that bounce off underground rock. The returning sound is picked up by the receivers and analyzed and mapped by computers. Mobile survey camps responsible for collecting seismic data are typically moved by D-7 Caterpillar tractors, although some of the tractors have been replaced by roller-tracked vehicles. Support vehicles shuttle to permanent facilities to deliver fuel and supplies.

Land-based two-dimensional (2-D) and three-dimensional (3-D) seismic surveys are done in winter when the tundra is frozen and snow-covered and when most animals have left an area, are in maternity dens, or are hibernating. Three-dimensional seismic lines usually are spaced a few hundred meters (several hundred feet) apart in grids. Lines in 2-D grids are spaced up to 10 km (several miles) apart. Today, 2-D surveys have been largely replaced by 3-D data acquisition. Because of the vulnerability of the tundra to disturbance of the organic mat and underlying permafrost, these off-road surveys have been restricted by the Alaska Department of Natural Resources. Seismic exploration is permitted when the ground is frozen to an average depth of 30 cm (12 in.) and when snow depth averages 15 cm (6 in.). From 1990-2001, 24,938 km (15,499 mi) of seismic lines was surveyed in northern Alaska.

Offshore vessels cruise similar grid patterns during the ice-free season, using high-pressure airguns instead of vibrators to generate sound waves. In the intermediate area of land-fast ice, seismic data often are acquired during winter with land-based instruments.

---

[1] On the North Slope, most oil production is on state land; leasing and exploration mostly occur on state and federal land. Some leasing, exploration, and production occur on Native land. The Arctic Slope Regional Corporation has subsurface mineral rights in some areas. The Beaufort Sea out to three miles is under state control; beyond that it is federal. Northstar is the only facility currently producing oil in federal waters off the North Slope.

Exploratory Drilling

After seismic surveys indicate that commercially feasible quantities of oil or gas are present, exploratory drilling begins. Today, onshore exploratory drilling is a winter activity based on ice roads and ice drilling pads; no permanent structures are built. In remote locations, an ice airstrip is built so that people and supplies can be flown to the site. In areas where prospects are closely spaced, or where confirmation wells are required, a single rig can drill 2 or 3 wells in a season. A typical exploratory well requires 14-45 days to drill.

Large amounts of water are used in these operations. Drilling a single exploratory well can use 5.7 million L (1.5 million gal); another 1.4 million L (360,000 gal) generally would be required for camp use. The Bureau of Land Management estimates that 3.8 million to 5.7 million L (1 to 1.5 million gal) of water is needed per mile to build an ice road 15 cm (6 in.) thick and 9-11 m (30-35 ft) wide (USACE 1998). Ice roads can extend for many kilometers, and they are increasingly used as a less expensive and less environmentally damaging alternative to gravel roads. For the winter of 2001-2002, 420 km (260 mi) of ice-road building was planned.

Offshore, exploration wells are drilled in the winter from ice islands, artificial gravel islands, natural islands, or drilling vessels or structures, depending on water depth and distance from the shore. Nearshore exploration—including most exploration in state waters—can be conducted from existing onshore facilities or from ice pads.

Exploratory drilling uses diesel engines to turn a drill bit, which cuts through the surface and the rock beneath. Drilling "mud" or fluid, a thick barite solution with various additives, is pumped down the center of the "drill string" (sections of pipe that are added as the bit descends). The mud returns to the surface in the space between the drill string and the casing for cleaning and re-use or for disposal.

Drill mud has three purposes. First, it lubricates the drill bit. Second, it brings the "cuttings," small pieces of rock that the bit grinds, to the surface. These are filtered at the surface and the mud is re-injected. Finally, the weight of the mud seals the well against pressure that is encountered in the well. Well casings, drill strings, mud, cement, diesel fuel, various types of equipment, and people are all transported to drill sites over ice roads or by aircraft.

In remote locations, such as the North Slope, oil-field activities require a concentrated work schedule. Commonly, workers meet and are transported to the drill site, where they stay for 1-2 weeks. Drilling continues around the clock, and two complete crews at the drill site rotate in 12-hour shifts. After 1 or 2 weeks of work, workers generally have time off, usually for the same period as the work cycle.

Development

Once an economically viable discovery is made, development begins. This phase involves additional drilling, and so begins construction of roads; airstrips; and waste-disposal, seawater treatment, gas-handling, power generation, storage, maintenance, and residential facilities (Figure 4-8). Most roads and other permanent facilities must be built on thick gravel pads, and pipelines and heated structures must be elevated on pilings to prevent thawing of the underlying permafrost and subsidence of the ground. Some 954 km (596 mi) of roads, 2,338 hectares (ha [5,777 acres]) of pads, and 116 ha (287 acres) of airstrips are spread across a contained development area of more than 2,600 km^2 (1,000 mi^2) of the North Slope, an area

FIGURE 4-8. Fields and Units, North Slope and Beaufort Sea. Drawing by Mapmakers Alaska 2002.

roughly as big as the land area of Rhode Island, which is 2,707 km^2 (1,045 mi^2). The area covered by gravel is about 3,700 ha (9,200 acres). This does not include the area covered by gravel fill or excavation for the Trans-Alaska Pipeline and Haul Road on the North Slope or the exploration facilities in the National Petroleum Reserve-Alaska.

Offshore gravel islands support production operations. Twenty such islands have been constructed in the Beaufort Sea (ADNR 2001a), including two at Endicott and one at the Northstar site. The Endicott islands are connected to each other and to the mainland by an 8 km (5 mi) causeway and are situated in waters generally less than 2 m (6.5 ft) deep (AOGA 2001). The 2 ha (5 acre) Northstar island site is located 6 km (4 mi) northwest of the Pt. MacIntyre field in 12 m (39 ft) of water (BP Northstar 2002).

The shallowness of the Beaufort Sea in the Prudhoe Bay prevents large vessels from docking there. Three gravel causeways have been constructed to facilitate docking, to provide access to artificial-gravel production islands, and to draw seawater for waterflooding. The causeways are 335 m (1,100 feet), 4 km (2.5 mi), and 8 km (5 mi) long, respectively (AOGA 2001).

Large quantities of gravel are required for building roads, and pads and for other purposes. From 1972 on, more than 56 million m^3 (73 million yd^3) of gravel (ADNR 2001b) was extracted from 24 open-pit gravel mines affecting some 2,546 ha (6,364 acres) of stream and river beds and upland sites on the North Slope (MMS 2001a; Gary Schultz, ADNR, personal communication, 2001). Similarly, construction and postexploration drilling require large amounts of water. Overall, the Alaska Department of Natural Resources (ADNR) estimates that 1.5 billion gal (5.7 billion L) of water was used by North Slope oil and gas operations in 2000 (ADNR 2000).

Facilities needed during development phase generally are constructed elsewhere, and transported to the North Slope on barges in late summer, and then moved by road to the pads. Workers and materials are brought in on the Dalton Highway or by air.

Production and Transportation

Production and transportation follow completion of development, but development activities often continue long after production begins. The major difference between this and the previous stages is that large volumes of fluids are handled, transported, and disposed. This phase involves drilling wells for enhanced oil recovery or waste disposal and the construction of pipelines to move oil, gas, "produced water" (water, often in very large volumes, that is extracted with the oil from a reservoir), and drilling wastes to the existing transportation infrastructure or to injection facilities. To maintain reservoir pressure, water is withdrawn from the Beaufort Sea and injected into oil-bearing formations. Because North Slope natural gas currently is uneconomical to market, gas that is not needed to fuel operations is injected back into the originating formation.

Until recently, gathering and distribution networks required gravel roads; currently those pipelines are built during winter via ice roads. All oil produced on the North Slope is fed through gathering lines to the Trans-Alaska Pipeline. The 1,300 km (800 mi) long pipeline leads to a tanker terminal in Valdez, on Alaska's south-central coast, from which oil is then shipped to refineries in the lower 48 states and, since 1996, in Asia.

On- and off-road vehicles, helicopters, fixed-wing aircraft, and seagoing vessels of various sizes transport equipment, materials, and people throughout the life of the oil field. Air, ground, and marine transportation needs are substantial. For example, the construction phase of the Northstar project involved about 35,000 surface trips by bus, truck, and other vehicles. Transportation needs drop dramatically after construction is complete.

Power generation and waste disposal continue throughout the life of an oil field. On the North Slope, power is generated by gas-fired turbines and heaters; diesel engines power most exploratory equipment as well as trucks, buses, and heavy equipment. These facilities and vehicles emit substantial amounts of air pollutants. Oxides of nitrogen (NO_x) constitute the largest single category of pollutants emitted. In 1999, oil and gas operations on the North Slope emitted some 70,000 metric tons [t]) of NO_x per year[2] (ADEC 2002). In 1994-1995, North Slope facilities[3] also emitted about 11,000 t of CO, 1334 t of SO_2, 5,400 t of particulate matter, and 2,400 t of volatile organic compounds during 1994-1995 (USACE 1999). Annual CO_2 emissions from Prudhoe Bay facilities are estimated[4] at 7.3 million t (Jaffe et al. 1995) to more than 40 million t (Brooks et al. 1997). Methane emissions have been estimated at 24,000 t (Jaffe et al. 1995). A final category of emissions is airborne particles, generated by construction activity and vehicular travel on gravel roads, than can significantly affect adjacent tundra.

Most North Slope waste is generated in exploration and production activities. More than 76,500 m^3 (100,000 yd^3) of solid waste is generated by oil-field operations on the North Slope each year (ADEC 2001, BP 1998). Waste includes oil-contaminated wastes, spill-cleanup materials, batteries, scrap metal, paper and polystyrene waste, tires, construction debris, wrecked vehicles, insulation, old drilling rigs, and food and domestic waste. These wastes are recycled, disposed of in the Deadhorse landfill, or incinerated. The North Slope Borough received 74,161 m^3 (97,000 yd^3) of waste in 2000. The committee did not have enough data to perform additional analyses.

Liquid wastes include sewage and domestic wastewater, desalination treatment discharges, and seawater-treatment-plant discharges. No data on the amount of liquid wastes generated by oil and gas operations on the North Slope were available to the committee (ADEC 2001). Treated sewage and domestic wastewater typically were discharged to tundra ponds or to surface impoundments until recently. Desalinated and seawater treatment wastewater are discharged to the ocean (ADEC 2001).

Waste associated with oil-field exploration, development, and production includes waste from drilling operations, which generate up to 1.1 million L (300,000 gal) of waste muds and "cuttings" per well (BP 1998); produced water, an average of 1.23 million barrels (bbl, 51.7 million gal, 196 million L) per day, typically containing a variety of organic pollutants and toxic metals (MMS 2000), usually reinjected; and "associated waste," which is other waste from oil or gas exploration and production—hydrostatic test fluid, oil and oily water, tank-bottom sludge, waste from well workovers and stimulations, pipeline pigging waste, and gas dehydration

---

[2] ADEC memo and spreadsheet, 5/17/02, ascribe 56,000 t to facilities emissions and 14,000 t to mobile sources.

[3] Includes emissions from Prudhoe Bay Unit western and eastern operating areas, Milne Point, Endicott, and Lisburne. Does not include Kuparuk, Alpine, North Star, Badami, or Pt. McIntyre, or any drilling or vehicle emissions (U.S. Army Engineer District, Alaska). Current allowable emissions are much higher for CO (18,040 t) and SO_2 (2,330 t) (Phillips, personal communication, 2001).

[4] Jaffe and colleagues (1995) calculated CO_2 emissions based on fuel use data reported to the state by the oil companies. Brooks and colleagues (1997) extrapolated observed emissions during 30 flights downwind of the oilfields. Their estimates were 6 times greater than those in Jaffe's report, and 4 times greater than total carbon emissions reported by oil facilities for the same months during which measurements were made.

wastes. In addition, the more than 9 t of waste generated each year on the North Slope that qualifies as hazardous, according to the Environmental Protection Agency (EPA) rules, is shipped to disposal facilities in the continental United States (BP 1998).

Generally, wastes are grouped as Class I (nonhazardous) or Class II (exempt) and are handled and disposed of in distinct classes of disposal wells. Oil-field wastes associated with exploration and production were specifically exempted from hazardous-waste regulation by Congress in 1980 (Section 3001 {b}[2](A), Resource Conservation and Recovery Act) regardless of whether that waste would otherwise meet EPA's criteria for hazardous-waste classification. The quantity of those wastes generated on the North Slope is unknown (ADEC 2001). Most of it is injected into subsurface formations.

Class I wastes consist principally of water and are considered nonhazardous. They are largely disposed of through injection into Class I disposal wells (Billington, Shafer, and Billington Environmental Consultants, unpublished, 1997), of which there are 7 in all, at Alpine, Badami, Prudhoe Bay, and Northstar (Maham 2001). The volume of fluid injected to date exceeds 12 million bbl (1.9 million L, 504 million gal). The principal injection horizons are porous Cretaceous sandstones at depths of 610-2,400 m (2,000-7,900 ft) that provide well-confined disposal zones. In the westernmost portions of the area, the formations are in the permafrost zone. The Alpine well injects wastes into formations at a depth of about 2,700 m (9,000 ft).

Class II wastes come directly from oil or gas wells. They include all produced fluids, muds, and associated wastes that have circulated in the well and solids and ligands that originate down-hole, such as formation water (BP 1998). Drilling muds are water-based materials with clays, weighting materials, and various additives. Cuttings are rock fragments derived from drilling the well. The cuttings are finely ground and injected with drilling muds. Produced water comes to the surface with oil and gas and must be removed before the oil can be sent to the Trans Alaska Pipeline. In 1998 (BP 1998), the volume of produced water was approximately 1.23 million bbl (196 million L, 51.7 million gal) per *day*—comparable to North Slope oil production. Most produced water is treated and re-injected into the reservoir; some is injected into approved disposal wells. The volume of associated wastes at the Prudhoe Bay field is approximately 1 million bbl (159 million L, 42 million gal) per year (API 1996). Class II wastes are injected into disposal horizons through 37 Class II disposal wells. More than 1.5 billion bbl (238 billion L, 63 billion gal) of produced water and associated wastes has been pumped into subsurface disposal formations.

Until recently, waste materials from the drilling of wells, including muds and cuttings, crude oil, spill materials, and other substances were disposed of in open gravel-bermed areas called reserve pits (BP 1998), that typically contained from 17 million to 51 million L (4.5 to 13.5 million gal) of waste (ADEC 1985). There were many problems with reserve pits however, including leaching of contents to the surrounding tundra. Disposal of accumulated pit fluid on roads for dust control or spilling directly on the tundra also has contaminated those areas. Studies by the U.S. Fish and Wildlife Service reported significant effects on water quality in nearby ponds (West and Snyder-Conn 1987, Woodward et al. 1988).

Under a consent decree reached between the industry and environmental groups, most old reserve pits in the Kuparuk and Prudhoe Bay fields are being cleaned out and the waste ground and injected into subsurface formations. In addition, ARCO and BP agreed to clean up 170 additional reserve pits as part of the charter agreement governing BP's acquisition of ARCO (BP Charter Agreement). A grinding and injection plant, the largest of its kind in the world, injected some 332,000 m^3 (434,000 yd^3) of reserve-pit solids in 2000 alone (Friar, personal communication, 2001).

The disposal process requires that porous, water-bearing formations below the surface casing accept fluids at pressures that will not propagate fractures through the upper confining zones. The disposal fluids must be compatible with the formation water, which must not be a potential source of drinking water.

CURRENT STRUCTURE OF THE NORTH SLOPE INDUSTRY

Historically, oil companies were directly involved in many of the physical aspects of the location, production, refinement, distribution, and sale of oil. Gradually, as the scale of oil and gas operations grew, more and more of the activities associated with the oil industry were contracted out to specialized service companies. In general, the major oil companies today own or control (lease) the mineral rights to the resource itself (oil or gas), the production facilities, and the pipeline distribution facilities (sometimes through cooperative ventures, as with the Alyeska Pipeline Service Company, a consortium of companies that operates the Trans Alaska Pipeline). Those companies also generally own or contract for other distribution networks (for shipping, for example) and refinery capacity, and they often franchise wholesale and retail distribution. Different service companies generally conduct seismic exploration, drill and complete wells, construct production facilities and pipelines, and supply technical experts to address most problems that occur during normal operation (down-hole problems, equipment failures, spills). In turn, many of those contractors subcontract to other specialized companies. For example, a drilling contractor could subcontract with other companies to support the drilling operation or provide food service, potable water, drilling mud, casings, drill strings, and even personnel. Many of those companies contract even further with other support companies that provide additional services.

If an exploratory well reveals the oil or gas is commercially feasible to extract, then the oil company will contract with fabrication companies to construct the various production facilities that are needed on land or off shore. In the case of the North Slope, those structures are fabricated in the continental United States or elsewhere in Alaska and shipped by barge to the North Slope during the open-water season. Then, a pipeline company connects the facility to the existing pipeline network, also supported by crews, fuel, water, pipe, and coating. If something breaks down during any of these operations, or if modifications need to be made, additional companies provide specialized services and tools. Once the oil is available for delivery, the oil company resumes control to produce and market the product.

NORTH SLOPE OIL-FIELD INFRASTRUCTURE

The history of the North Slope road and infrastructure network is traced in Tables 4-2, 4-3, and 4-4 and in a series of maps (Figures 4-3, 4-4, 4-5, 4-6). A full description of the mapping and tabular analyses is contained in Appendix E. The analyses were done by Aeromap, Inc. using information provided by BP and from other sources. The tables show North Slope oil-field infrastructure history by year and geographic area. Numbers are cumulative. Dashes are used if there were no data for a given year. Figures have been rounded, and may not add exactly in all cases. Exact figures and category definitions are detailed in Appendix E.

Table 4-2 Point Measurements

	1968	1973	1977	1983	1988	1994	2001
Gravel pads							
Production pads, drill sites	0	16	22	62	95	104	115
Processing, facility pads	0	6	10	14	18	18	20
Support pads (power stations, camps, staging pads)	1	36	63	98	108	113	115
Exploration sites	3	42	63	103	104	106	103
Offshore exploration islands	0	0	2	12	13	13	13
Offshore production islands	0	0	0	0	2	3	4
Airstrips	1	11	15	16	16	16	16
Exploration airstrips	0	4	4	4	4	4	4
Culverts	-	-	-	-	-	-	1395
Bridges	-	-	-	-	-	-	17
Caribou Crossings	-	-	-	-	-	-	50
Landfills	-	-	-	-	-	-	1

Table 4-3 Infrastructure Length (Miles)

	1968	1973	1977	1983	1988	1994	2001
Roads	0	100	139	294	358	370	400
Peat roads	30	101	101	101	96	96	96
Causeways	0	0	2	3	8	8	8
Tractor trails, tundra scars	19	54	59	57	57	57	56
Exploration roads	0	36	36	36	36	36	36
Total road length	49	290	336	491	554	566	596
Pipeline corridors							
1-5 Pipes per bundle	-	-	-	-	-	-	366
6-11 Pipes per bundle	-	-	-	-	-	-	73
12-17 Pipes per bundle	-	-	-	-	-	-	6
18-26 Pipes per bundle	-	-	-	-	-	-	4
Total pipeline length	-	-	-	-	-	-	450
Power transmission lines	-	-	-	-	-	-	219

Table 4-4 Infrastructure Area (Acres) (not including Dalton Highway)

	1968	1973	1977	1983	1988	1994	2001
Gravel roads and causeways							
roads	-	677	1002	2029	2448	2536	2745
causeways	-	0	48	82	235	229	227
Total gravel road and causeway area	-	677	1050	2110	2683	2765	2971
Airstrips (gravel or paved)	6	136	252	287	313	313	287
Offshore gravel pads, islands							
Exploration islands	0	0	5	54	57	57	53
Production islands	0	0	0	0	76	92	101
Total offshore gravel pad, island area	0	0	5	54	133	149	155
Gravel Pads							
Production pads, drill sites	0	276	647	2199	2917	3019	3126
Processing facility pads	0	74	390	692	874	890	917
Support pads (camps, power stations)	14	441	769	1340	1444	1470	1463

Table 4-4 (continued)

Exploration site	0	109	175	339	317	314	305
Total gravel pad area	14	901	1981	4570	5552	5692	5817
Total gravel footprint	20	1713	3288	7022	8681	8919	9225
Other affected areas							
Exploration site-disturbed area around gravel pad	55	346	467	613	627	650	645
Exploration airstrip-thin gravel, tundra scar	0	68	68	68	68	68	67
Peat roads	143	547	546	546	520	517	517
Tractor trail, tundra scar	110	250	272	263	258	258	258
Exploration roads-thin gravel, tundra scar	0	177	179	177	178	178	177
Gravel pad removed, site in process of recovery	0	1	21	27	46	81	100
Gravel pad removed, site is recovered	-	-	-	-	-	-	95
Total other affected area	308	1388	1552	1694	1698	1753	1765
Gravel mines							
In rivers	25	4732	4996	5011	5063	5061	5082
In tundra	0	34	151	745	1179	1186	1283
Total Gravel Mine Area (acres)	25	4766	5146	5756	6241	6246	6364
Total Impacted Area (acres)	353	7868	9987	14472	16620	16918	17354

The development history of the road network and gravel pads was traced in a series of aerial photographs taken in 1968, 1973, 1988, and 2001. The length of the roads and the area of roads, pads, gravel mines, and some other affected areas were determined for each year. The analysis was divided into four major areas:

- The area between Foggy Island and the Kuparuk River contains the main Prudhoe Bay oil field, Lisburne, Niakuk, Endicott, and several smaller oil fields. This area generally represents the technology used to construct the early oil fields.
- The area between the Kuparuk River and Kalubik Creek contains the Kuparuk and Milne Point fields represents an intermediate era of oil-field technology.
- The area between Foggy Island Bay and the Canning River contains the Badami oil field and a few remote exploration sites.
- The area between Kabulik Creek and the Colville River contains the Meltwater, Tarn, and Alpine oil fields. Badami Alpine, and Tarn are the newest oil fields, and they represent newer technology.

The portion of the oil-field network that is connected by roads stretches to 97 km (60 mi) from the Endicott field in the east to the Tarn oil field in the west. The gravel road network expanded during the past 33 years from a 79 km (49 mi) network of peat roads and tractor trails in 1968 to the current 960 km (596 mi) network of gravel roads and abandoned roads and trails (Figure 4-9). Most of the expansion of the road network was done before 1988, the development phase of the field, during which the rate of growth was about 40 km (24 mi) per year. Since 1988, the rate of growth in the road network has been about 5.3 km (3.3 mi) per year. The currently used portion of the network consists of 640 km (400 mi) of gravel roads. About 350 km (215 mi) of the gravel road network is associated with the Prudhoe Bay oil field and with other fields between the Kuparuk and Sagavanirktok rivers. There is 293 km (182 mi) of road in the oil fields west of the Kuparuk River. The newest extensions to the road system have been mainly winter ice roads to link new drill sites in the National Petroleum Reserve-Alaska and elsewhere, but 32 km (20 mi) of new road built since 1998 connects to oil fields southwest of

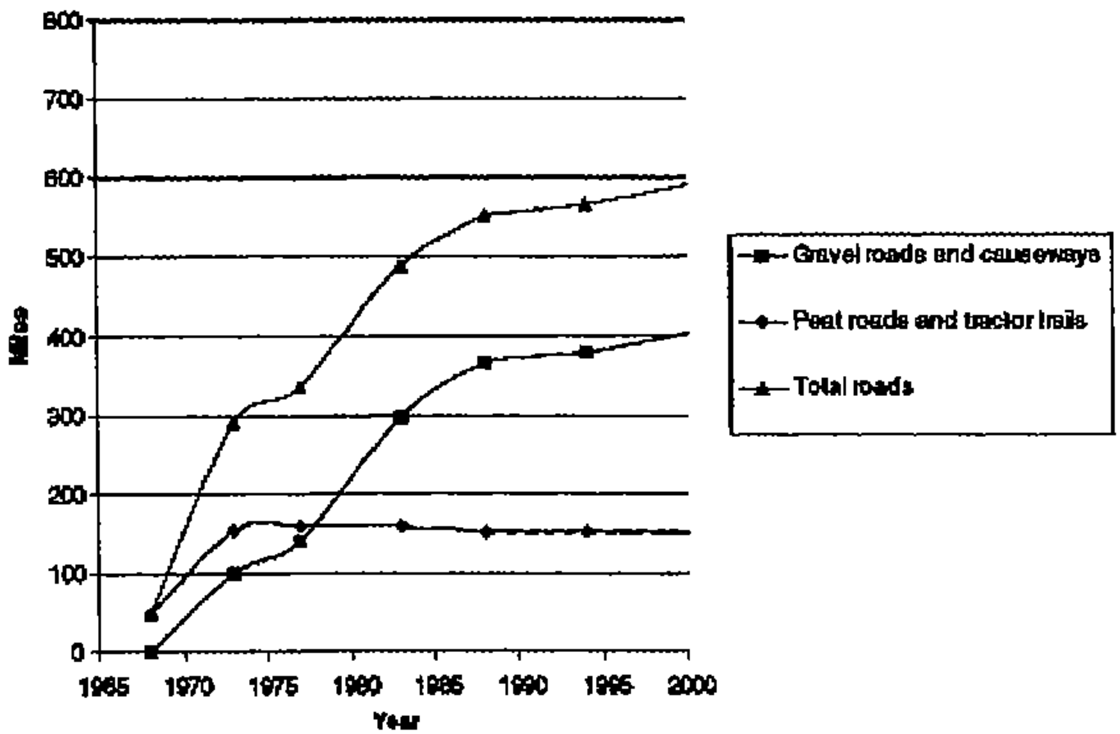


FIGURE 4-9. History of roads in the North Slope oil fields. Early roads, including tractor trails and peat roads, are indicated with circles. The squares are the existing length of gravel roads. Dalton Highway ont included. Source: Alaska Geobotany Center, University of Alaska Fairbanks 2002.

The total gravel-covered area increased from about 8 ha (20 acres) in 1968 to about 4,000 ha (9,200 acres) in 2001 (Figure 4-10). The rate of gravel placement declined noticeably after 1988, because the main road network and most of the pads in the Prudhoe Bay and Kuparuk oil fields had already been built. The average rate of growth was 320 ha (780 acres) per year before 1988 and 23 ha (57 acres) per year after 1988. Most of the gravel-covered areas are associated with onshore drilling and construction pads (2,338 ha [5,777 acres]). The rest is in roads and causeways (1,204 ha [2,974 acres]), airstrips (108 ha [267 acres]), and offshore gravel pads and islands (63 ha [155 acres]). Other mapped disturbances include gravel mines (2,575 ha [6,363 acres]) and exploration pads and airstrips, peat roads, and exploration trails (714 ha [1,765 acres]) (Figure 4-11). Gravel consumption from state lands on the North Slope is shown in Table 4-5. The 1.2 million m^3 (1.5 million yd^3) mined (5 million yd^3 permitted) for Alpine from Native corporation lands is not included.

Table 4-5 North Slope Gravel Consumption, 1974-1999*

Years	Permits Issued	yd^3 Permitted	yd^3 Extracted
74-79	7	15,408,445	11,415,693
80-84	52	73,312,099	39,218,481
85-89	12	10,767,800	3,640,448
90-94	18	3,328,500	1,254,821
95-99	22	5,704,100	2,326,820
00-01	12	4,384,500	24,218

Source: ADNR (1 yd^3 is equal to 0.765 m^3)
*Trans Alaska Pipeline and Haul Road not included; 00-01 data incomplete.

There are 115 gravel drill sites or pads, 20 pads with processing facilities, 115 pads with other support facilities (power stations, camps, staging pads), 91 exploration sites, 13 offshore exploration islands, 4 offshore production islands, 16 airstrips, 4 exploration airstrips, 1,395 culverts, 960 km (596 mi) of roads and permanent trails, 725 km (450 mi) of pipeline corridors (containing 2,720 km [1,690 mi] of pipe), and 353 km (219 mi) of transmission lines.

The Aeromap analysis did not address the areas indirectly affected—seismic trails, ice roads, or off-road vehicle tracks—nor did it identify the types of terrain that were affected by different activity or use. Those issues are discussed in Chapter 7. It also did not cover the Trans-Alaska Pipeline, the National Petroleum Reserve-Alaska, and other areas of the North Slope; the analysis is provided as an example where good information is available and where most of the development has occurred. Much of that development used technology no longer in use.

RECENT TECHNOLOGY DEVELOPMENTS

Over the past two decades, new technologies have been developed and applied to exploration, development, and production on the North Slope. Some technologies, such as the use of ice roads and ice pads for exploration wells and the Arctic Drilling Platform, are unique to the Arctic and were largely developed in Alaska. Other advances, such as the use of coiled tubing, 3-D seismic-data acquisition, horizontal and multilateral drilling, measurement while drilling, low ground-pressure vehicles (Rolligons), and remote sensing, were developed

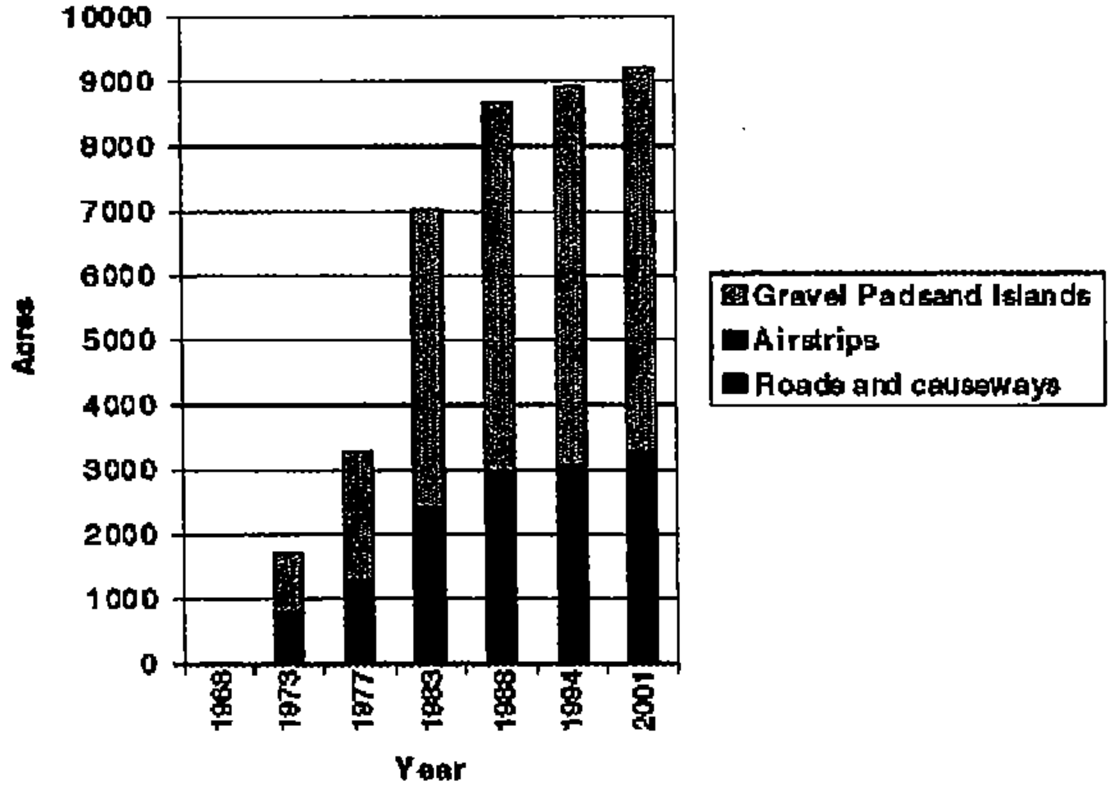


FIGURE 4-10. History of gravel placement. The area of gravel pads includes all exploration sites, drill sites, production pads, and support pads (camps, power stations). Gravel islands include offshore exploration and production islands. Dalton Highway and Trans Alaska Pipeline not included. Source: Alaska Geobotany Center, University of Alaska Fairbanks 2002.

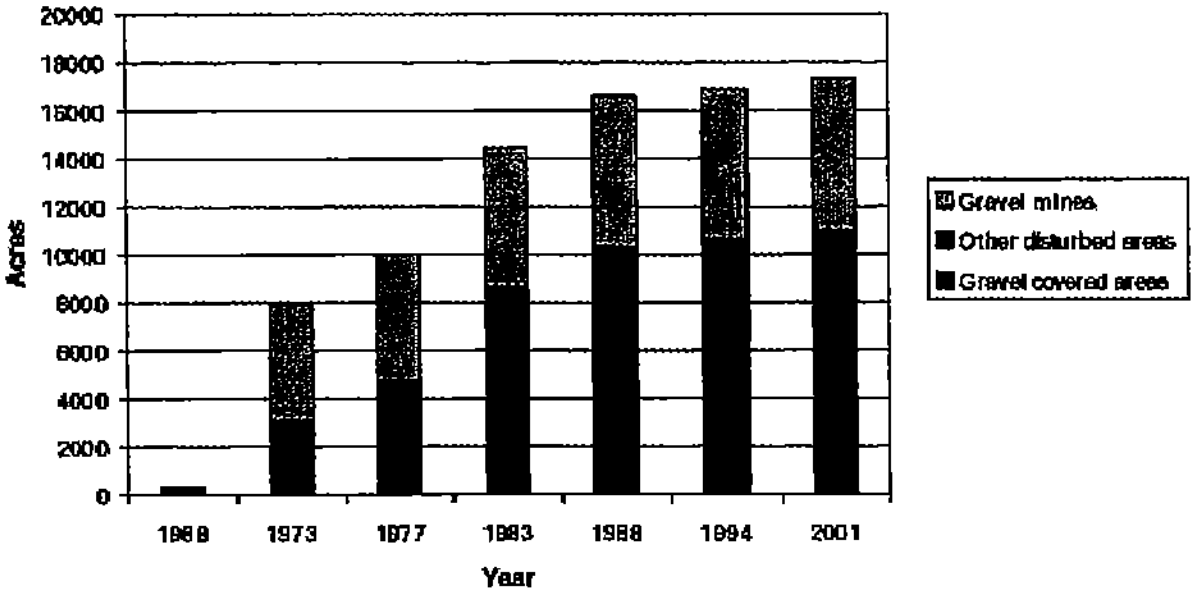


FIGURE 4-11. History of total disturbed area. The gravel-covered areas portion of each bar is equivalent to total gravel placement in Figure 4-10. Other areas include disturbed areas around exploration sites, exploration airstrips with thin gravel, peat roads, tractor trails, and exploration roads. Seismic exploration trails, ice roads, and off-road vehicle tracks are not included. Gravel placement and the resulting total direct disturbance leveled off after 1988. Source: Alaska Geobotany Center, University of Alaska Fairbanks 2002.

elsewhere and adapted for use on the North Slope. Although some of those newer technologies have been used extensively, and the newer fields (such as the one at Alpine) use them almost exclusively, older technologies are still integral parts of the older portions of the Prudhoe Bay and Kuparuk fields.

The new exploration-related technologies have reduced the overall use of gravel and presently eliminated it from the exploration-drilling process, have provided data for better siting of facilities, and have reduced the number of wells required to find and evaluate a new field. Although the physical effects have been greatly reduced by the use of these technologies, there are still valid concerns regarding the potential for some amount of damage to the environment. In addition, changing climate might reduce the utility of some newer technologies in some circumstances.

The environmental effects of the older road and pad construction techniques and seismic trails are matters of genuine concern. In some instances, the effects have not diminished with the passage of time; in others, a natural but slow recovery is occurring. The visual impact in some cases will be evident for years-if not for decades.

The density of 3-D seismic activities can cause short-term visual impact. In areas where there is little snow cover or steep vegetated terrain, damage to the tundra and shrubs can be locally significant and long lasting. Long-term studies of the trails built for the closely spaced 3-D acquisitions are required to document the potential effects.

The introduction of newer technologies has reduced the amounts of water and gravel required for some types of operations because of their more efficient well operations and smaller pad sizes. The greater reach of horizontal wells and the use of multilateral drilling reduces the need for large pads and it allows extraction of oil from larger areas; thus reducing the number of pads required to develop an oil field. Because the fields use more effective drilling and fewer wells, the quantities of waste, mud, and cuttings are smaller. Because fuel consumption is lower, there are fewer emissions.

Environmental damage continues to be associated with the use of raw materials and resources, such as gravel and water. And their extraction and use will continue, although at reduced rates per unit of oil recovered because 3D seismic technology reduces the percentage of dry wells. Also, it is possible that ice pads will be superseded by new types of drilling platforms, and by use of Rolligons. Gravel mining and tundra coverage and water use for ice roads or pads, drilling mud, and the like are expected to continue for the foreseeable future. Any risk associated with well drilling remains, although ameliorated somewhat by newer drilling and completion technologies. The possibility of losing a tool downhole, of mud or cuttings spills, and of emissions of air pollutants will continue to exist—if to a lesser extent than in the past. A reduction of ground traffic is likely to result in an increase in aircraft movements.

Absent new technological advances, the pipelines must be above the ground; if they are buried, they could lose support by thawing permafrost (Chapter 6). Increasing their elevation has facilitated the movements of caribou, and remote monitoring of pipelines has lessened the probability of spills. Remote-sensing techniques have improved early detection and tracking of spills, and have helped with recognition of key habitat for caribou. As a result, facilities could be located to minimize impacts on sensitive caribou populations.

Some consequences of using newer technologies also can threaten the environment. Any spills associated with pipelines buried deeply under river crossings would be difficult to clean up and might damage those rivers. There is a remote possibility that injection of waste into subsurface disposal zones could contaminate a potential groundwater source, or locally overpressure an interval and result in an escape of fluid to the surface. A poor cement or casing job could provide an avenue of escape for annular injected wastes. The newer technologies have resulted in increased protection for the environment, but they have not eliminated the potential for accidents. Appendix D offers a more complete discussion of the technologies and their consequences.

HOW OIL-FIELD ACTIVITIES CAN AFFECT THE ENVIRONMENT

This section describes briefly how the activities of an oil field can affect the environment. Assessments of the effects of those activities and how they accumulate, which requires analyses of the effects on various receptors, are presented in Chapters 6 through 9.

Oil and Seawater Spills

Accidental spills of crude oil, petroleum products (such as diesel fuel or crankcase oil), and saline water (produced with the oil or seawater used in enhanced oil recovery operations) occur on the North Slope. No large oil spills (more than 1,000 bbl (159,000 L, 42,000 gal) have occurred on land on the North Slope as a result of exploration and production operations, although many smaller spills have occurred. Three major spills have occurred from the North Slope segment of the Trans Alaska Pipeline. No major offshore oil spills have been reported. Many saline water spills have occurred on land. Most crude oil, petroleum products, and saline water spills were confined to gravel pads and roads. Some have affected small areas of tundra, resulting in long-term damage.

Spills can occur at and around exploration and production facilities, pipelines, and pump stations; at support facilities, such as storage tanks; and from various vehicles in the area. Oil spills on the North Slope have ranged from 0.006 bbl to 925 bbl (0.98-14,703 L, 0.26 to 38,850 gal). Each year from 1977 to 1999 there was an average of 234 spills of crude oil and petroleum products associated with exploration and production activities on the North Slope. The annual average spill volume was 537 bbl (85,376 L, 22,554 gal). The annual average during that period was 69 spills of crude oil and products associated with the operation of the Trans Alaska Pipeline from Pump Station 1 to Atigun Pass. The average annual spill volume was 265 bbl (42,132 L, 11,130 gal).

Information on seawater spills is less complete (Maxim and Niebo 2001a). From 1986 through 1999, there were 929 seawater spills associated with North Slope exploration and production and the North Slope portion of the pipeline (up to Atigun Pass). In all 40,849 bbl (6 million L, 1.7 million gal) of seawater was spilled during the period, for an average of 66 spills per year with an annual average volume of 2,918 bbl (463,923 L, 122,556 gal). A detailed analysis of spills, including their causes and frequency, the fate and effects of spilled material, and remediation, is in Appendix G.

Seismic Exploration

Seismic exploration is usually done by sending sound waves into the substratum and deducing information about its oil-bearing potential based on the speed and strength of the returning echoes. On land, the vehicles that transport the testing equipment can affect the tundra and leave tracks that can persist for years and be visible from considerable distances, especially from the air. Vehicle traffic can disturb denning polar bears and muskox herds. Offshore, seismic exploration can affect the distribution and migration of marine animals.

Mining and Redistribution of Gravel

As described above, gravel is used for roads, causeways, pads, islands, and other structures. The gravel is obtained locally, primarily from river beds and gravel pits excavated into the tundra. Its removal and redistribution affect drainage patterns, flow volumes, melting and freezing of the active layer, movements of humans and animals, the visual landscape, and snow accumulation. Gravel also kills the vegetation it covers.

Freshwater Use and Redistribution

Fresh water is used in the construction of ice roads and pads and in oil fields. An annual average of 4.4 billion L (1,163 million gal, range: 776-1,458 million gal) was used this way between 1996 and 2000 (Table 4-6). Removing water from lakes can change their character, especially if the water that remains is so shallow that the lake freezes to the bottom. Removal and redistribution of water can affect the organisms that depend on it for habitat, migration, food, and safety (Chapter 8).

Table 4-6 Quantity and Source of Current North Slope Freshwater Use in Established Oil Fields

Source	Field, Activity, or Operator	1996	1997	1998	1999	2000
Surface water						
	Prudhoe Bay					
	East	181	189	112	95	108
	West	132	130	140	92	61
	Kuparuk*	159	78	127	96	181
	Alpine*	0	0	150	244	213
	Milne Point	38	51	40	11	28
	Endicott	0	0	3	0	5
	Badami	0	10	22	9	1
	Northstar	6	1	5	0	8
	BP exploration	3	36	31	40	4
Total surface water		519	495	630	587	609
Number of lakes		125	131	154	181	174
Deep Wells and Other Sources		257	606	681	582	849
Total Water Use		776	1,101	1,311	1,169	1,458

(Millions of gallons)
*Includes exploration.

Source: Data compiled for this report by BP Exploration (Alaska), Inc., with assistance from Alaska Department of Natural Resources and Phillips Alaska, Inc.

Seawater Use and Diversion

Large amounts of seawater are withdrawn from the coastal region and injected into subsurface formations to maintain or enhance pressure in the formation for oil recovery (Table 4-7). The four existing intakes can remove almost 600 million L (158 million gal) of seawater per day, and between 1996 and 2001, they removed a daily average of 174 million L (46 million gal). Longshore currents have been altered by coastal structures, such as causeways, and those alterations can affect migrations of fish and perhaps other animals. In the summer, onshore seawater spills kill vegetation.

Table 4-7 Intake Capacity and Use of seawater by North Slope Facilities

Facility	Intake Capacity	1996-2001 Mean
Prudhoe Bay Unit waterflood	103.6	26
Kuparuk waterflood	28.2	13
Endicott waterflood	23.5	7
Northstar	2.6	0.05
Totals	157.90	46.05

Millions of gallons per day.
Source: Data compiled for this report by BP Exploration (Alaska), Inc., with assistance from ADNR and Phillips Alaska, Inc.

Sea Ice Structures

Exploration and development in nearshore and offshore waters of the Beaufort Sea require a variety of temporary and permanent structures, such as causeways, islands, and drilling platforms. A major concern about causeways is their potential to alter nearshore currents and fish migrations. Drifting ice accumulates on the up-current sides of gravel causeways, islands, and drilling platforms, and areas of open water (polynyas) form on the down-current sides (Stirling 1988a). Gravel structures and grounded ice roads and islands can affect the stability and persistence of shore-fast ice when they serve as anchoring points or cause cracks and leads to form in the ice sheet.

Construction, Presence, and Aging of Infrastructure

The traffic and noise associated with the construction of infrastructure—roads, pipelines, buildings, pads, platforms, airstrips—can disturb or alter animal migration. In addition, the presence of structures themselves on the landscape can disrupt migration and thus alter the distribution of organisms. The presence of infrastructure affects the amount and distribution of dust and ambient noise; it also affects air quality, either directly (by emissions) or indirectly (by providing a substratum for the movement of emitting vehicles and supporting the construction of emitting structures). There are visual consequences as well: The structures change the way the landscape is perceived by residents, visitors, and transients. Finally, roads and airstrips affect the environment by increasing access to it and thus by increasing the intensity of the effects of human activities in time and space.

As the infrastructure ages or is abandoned, other unintended environmental effects can result. Aging increases the likelihood of failure, which can lead to accidental discharges (spills) or to other accidents, such as fires. Abandoned roads and other structures can degrade from melting permafrost and continue to alter the visual environment, especially if the climate continues to warm.

Most North Slope oil-field equipment dates from the last quarter of the 20th century. It will continue to age over the next 25 years, the period of this report's scope. Components that could fail include pipelines through corrosion, subsurface safety valves, and safety systems to suppress fires and explosions. The older oil-field areas such as Prudhoe Bay will be most susceptible to aging. Thus, age-related maintenance demands will increase as oil revenues from declining oil fields decrease. As an aging field's production declines and the cost of extracting oil increases, the economic incentive to postpone or eliminate maintenance and replacement will increase. The environmental effects of aging infrastructure will depend on interactions between the economics of declining fields, increased replacement and maintenance costs, the regulatory regime, and other factors equally hard to predict.

Transportation

Noise and disturbances from water, air, on-road, and off-road transportation of machinery, materials, and people can significantly affect marine and terrestrial animals and people's experiences in the environment.

Waste Disposal

Disposal of large amounts of industrial and domestic waste produced by industrial operations can contaminate environments and affect the population dynamics of animals, both positively, by providing food, and negatively, by contaminating environments.

Redistribution of Wealth

Oil and gas activities bring money to the North Slope both directly and indirectly. They provide jobs and tax revenues, and they fuel demand for local goods and services. They attract tourists, regulators, government officials, members of the news media, scientists, and others, and those visitors contribute to the local economy. The oil industry had a significant effect on changing the social structure of North Slope communities from subsistence alone to a mixed subsistence-cash economy. A variety of organizations have been established as a result of oil and gas activities—the Arctic Slope Regional Corporation, the Kaktovik Inupiat Corporation, and various government departments of the North Slope Borough and communities. Those organizations have made, lost, and spent money.

Information Dissemination

Oil, gas, and related activities disseminate a great deal of information. For example, lease sales are announced, oil finds are announced, and the expected methods of extraction are described; scientific studies are conducted and published; political discussions are held; laws and regulations are considered and passed or rejected. All of this information has profound direct and indirect effects on North Slope residents. The announcement of a lease sale can cause fear of environmental damage at the same time it raises expectation of profit from private land sales or an influx of new jobs. As a result, investment decisions, lifestyle changes, and the way people spend their time and energy can be substantially altered. Scientific studies can confirm or contradict people's opinions, knowledge, hopes, and fears. Political discussions can change perceptions, behavior, investments, and mental health.

These effects of information dissemination—even in the absence of physical activity—are as real as and often even more important than the direct effects of physical activities such as construction of infrastructure.

5

Future Oil and Gas Activities

The directive to the Committee on Cumulative Environmental Effects of Alaskan North Slope Oil and Gas Activities included assessing the likely future cumulative effects of industrial activities that have occurred on the North Slope and the cumulative effects of future industrial activities. All projections of activities and the accumulation of their effects are uncertain because many factors, some of which are highly unpredictable, will influence the location and extent of exploration for and extraction of oil and gas on the North Slope. For example, extraction and marketing of oil depend on the price of oil, which in turn depends on the ability of the Organization of Petroleum Exporting Countries (OPEC) to maintain high prices for oil on the world market. Wars or terrorist activities could dramatically alter all industrial activities on the North Slope.

Nonetheless, without a plausible scenario the committee could not make substantial progress in predicting cumulative effects on the physical and biologic systems of the North Slope. We therefore evaluated the consequences of a development scenario that assumes a continuing.favorable market price for oil and "normal" international relations during the next several decades. Such a scenario is plausible even though the probability of its occurrence cannot be determined.

PLAUSIBLE SCENARIO

Even if prices and political stability were to continue to favor exploration and extraction of North Slope oil and gas, many variables bear on the amount of activity and the success of future exploration and development: land availability, the regulatory environment, pricing, technology, exploration concepts, competition, and infrastructure.

The committee's scenario is based on the way the petroleum industry operates now, and it assumes a continuation of trends, as indicated by recent activities and the actions undertaken or supported by the key federal and state oversight agencies. Exploration in the 1002 Area of the Arctic National Wildlife Refuge (see Figure 3-1) is not considered because it is currently prohibited. However, the area is included as a possible additional and potentially significant component of the recoverable oil reserves on the North Slope in case exploration there is approved by Congress. The scenario has a list of important assumptions:

- Oil prices will remain high enough to support continued exploration and development.

- Climate change will not be so great during the next 50 years as to render current exploration methods obsolete or foreclose modifications, such as use of Rolligons and new drilling platforms.
- All new exploration and development activities will use technologies at least as good as those in use at Alpine.
- Offshore exploration (and probable extraction) will continue, but at a slower pace, along the Beaufort Sea coast from Point Barrow to Flaxman Island and possibly eastward to the Canadian border.
- Onshore exploration (and probable extraction) will continue both southward into the foothills of the Brooks Range and westward well into the National Petroleum Reserve-Alaska.
- Gas will become a significant component of exploration and development activity, and a gas pipeline will be built.
- The number of exploration companies, especially with gas interests, will expand and competition will increase.

The committee's projection assumes significant new discoveries and developments and a gradual decline in output from older oil fields. This in turn is likely to influence development of satellite fields. We assume there will be significant oil discoveries in each of the exploration subprovinces, with the possible exception of the southern area of the National Petroleum Reserve-Alaska, where gas deposits are more likely to be recoverable. We consider the probable exploration and development activities from the present to 2050.

Exploration Provinces

Our forecast separates potential activity in three major operating provinces that correspond to the jurisdictional framework within which future developments are likely: the state and native lands of the Colville-Canning Province, the Beaufort Sea, and the federal lands of the National Petroleum Reserve-Alaska. These subdivisions are under the jurisdiction of different regulatory agencies, and they have different leasing schedules, regulatory regimes, infrastructure needs, and resource potential. The Beaufort Sea is considered as two subunits, the federal outer continental shelf (OCS) and the shallower state nearshore area. The National Petroleum Reserve-Alaska and Colville-Canning are subdivided into gas- and oil-prone subprovinces.

Three related sets of units of measure are often used in discussions about oil reserve or resource estimates: original oil in place (OOIP), technically recoverable reserve (TRR), and economically recoverable reserve (ERR). Gas reserves are treated similarly. OOIP estimates the volume in a reservoir or reservoirs before production starts. It does not represent the quantity that can be produced from the field. OOIP at Prudhoe Bay was approximately 23 billion barrels (bbl). (A barrel is 42 U.S. gallons, or 159 L). TRR is the volume of oil or gas that is recoverable—independent of price. ERR, that portion of TRR that it is feasible to recover, is sensitive to price and technology. The current ERR estimate for the Prudhoe Bay field is 13 billion bbl. Under ideal conditions ERR approaches TRR, but rarely does a reservoir yield an ERR that exceeds 0.5 times that area's OOIP.

It is important to distinguish such estimates when reading published information about oil and gas reserves. The numbers that industry releases or discusses for new discoveries or existing fields generally are ERR values. The federal agencies and other groups that perform public domain assessment of oil and gas reserves, as in the Arctic National Wildlife Refuge and the National Petroleum Reserve-Alaska, generally present their results as TRR. For example, in the 2002 appraisal of the National Petroleum Reserve-Alaska, the USGS provided a mean reserve estimate of 9.3 billion bbl of TRR. They then may give an estimate, as a function of assumed oil price ranges, of ERR. In the 2002 National Petroleum Reserve-Alaska appraisal ERR was estimated to range between 1.3 and 5.6 billion bbl of oil over a range of market prices between $22.00 and $30.00 per barrel.

Once production has been established in an area, with the discovery of a large commercial accumulation of oil or gas, other adjacent, previously technically recoverable but uneconomic, small accumulations become economic despite a relatively low oil or gas market price. This is because the investment in the necessary production and transportation infrastructure has been justified by the discovery of the large field. Examples are the Midnight Sun oil field north of Prudhoe Bay and the satellites north and south of Alpine. The Midnight Sun field is a 20- to 40-million-barrel field that would have no stand-alone economic value. The presence of the Prudhoe Bay field and its infrastructure turns several millions of barrels of technically recoverable reserves into economically recoverable reserves. The same holds true for the Alpine field and its satellites. Much of the current activity in and near the major North Slope fields is related to the development of these small accumulations.

In many of the following sections, two sets of reserve numbers are given. The intent is to provide TRR estimates made by various groups or agencies for these exploration provinces and then to present possible volumes of ERR additions for comparison with the produced volumes and remaining known reserves in the discovered fields. ERR estimates are based on the scenario assumptions presented above and reflect OOIP or TRR volumes, or both.

Reliable estimates for the remaining potential for oil and gas on the North Slope are not available because of a lack of resource evaluations based on current geological knowledge. One recent estimate (Coleman et al. 2001) placed future TRR volumes for the Brooks-Colville system of the North Slope at 14 billion bbl of oil and 32.8 trillion cubic feet of gas (TCFG). The information available indicates that those estimates include the Arctic National Wildlife Refuge. They do not allow for significant reserves in the non-refuge portions of the North Slope, which include all of the National Petroleum Reserve-Alaska, the currently underexplored and nonproductive portions of the Colville-Canning Province, and the Beaufort Sea. The numbers are probably conservative given recent discoveries in and near the National Petroleum Reserve-Alaska and the size of the U.S. Geological Survey (USGS) estimates for the Arctic National Wildlife Refuge.

Older estimates for the entire North Slope and the state waters of the Beaufort Sea range from mean undiscovered TRR of 12.6 billion bbl of oil and 54.1 TCFG (Magoon 1994) to a TRR of 18 billion bbl of oil, exclusive of Arctic National Wildlife Refuge reserves (Anonymous 1991). The disparity in those numbers generates confusion about the magnitude of the remaining undiscovered reserves on the North Slope and the adjacent Beaufort Sea. (Note that the numbers do not include the federal OCS portion of the Beaufort Sea.) Gas has frequently been ignored or downplayed in the resource assessment process, but it has gained new emphasis since the construction of a gas pipeline has garnered renewed support.

The last thorough assessments of those areas, exclusive of the Arctic National Wildlife Refuge, were completed in 1978 and 1980, and USGS is currently reevaluating the estimates. Resource evaluations for the National Petroleum Reserve-Alaska were compiled in May 2002

(Bird and Houseknecht 2002). For the rest of the North Slope, they are expected in late 2003 or early 2004 (Bird 2001).

Colville-Canning Province

This area includes all lands between the Colville and Canning rivers, from the Beaufort Sea south to the northern limits of the Gates of the Arctic National Park and Arctic National Wildlife Refuge. The bulk of the area is state owned, but the Arctic Slope Regional Corporation (ASRC) controls nearly 1.2 million hectares (ha, 3 million acres) in the Brooks Range foothills. Lease sales have been held in the area since 1958, with 4 federal sales and 28 state sales. Hundreds of wells have been drilled, most of them in the major fields of the northern portion of the area; ERR of 17 billion to 18 billion bbl of oil and more than 35 TCFG have been found. The major oil discoveries include the Prudhoe Bay, Kuparuk, Endicott, Point McIntire, and Alpine fields as well as numerous small satellite fields. Prudhoe Bay and Point Thomson are the sites of the principal gas accumulations. All of these fields are in the northern area, on or near the Barrow Arch. Farther to the south the source rocks and reservoirs are deeply buried and are generally too mature to contain oil. This southern gas-prone region is called the Brooks Range foothills belt. Based on the presence of 35 TCFG in the area of the developed and developing fields, it is obvious that the oil-prone area also has significant gas resources. The converse is not necessarily true. The oil potential of the foothills belt could be modest at best.

Northern Colville-Canning

This area, between Canning and Colville rivers, extends south from the Beaufort Sea coast to approximately 69° 45′ N latitude and has been the focus of most of the exploratory drilling and oil development on the North Slope since 1969. All of the onshore producing oil fields are located here.

The area is expected to continue to be one of the most active regions of the North Slope, at least for the near-term, as major producers add production through the discovery of new medium-sized oil accumulations and the development of satellite fields. If the economic indicators continue to be favorable, gas pipeline and gas-producing facilities could be brought online by 2010. If so, gas exploration would become routine. The expansion of the gas-producing and gathering system would continue into the early 2020s. Most of the attractive area would be leased by 2010 and fully developed by 2030. The existing fields and infrastructure should continue be the backbone of North Slope production, either directly or indirectly, by supplying the facilities to allow nearby, otherwise uneconomic, oil and gas accumulations to be developed. If so, oil production could continue well into the second quarter of the twenty-first century; gas production could go until 2040-2050. Future reserve additions should be approximately 2.5 billion to 3 billion bbl of oil with the possibility of two to three times that quantity if new technologies result in increased recovery from the West Sak and Ugnu heavy oil reservoirs. The potential for additions to the gas reserve base is 10-15 TCFG.

Brooks Range Foothills Belt

The Brooks Range foothills belt extends south from approximately 69° 45′ N to the northern boundary of the Arctic National Wildlife Refuge and Gates of the Arctic National Park and lies between the refuge and National Petroleum Reserve-Alaska. ASRC lands are included with the state area discussion.

The total area is about 4 million ha (9.8 million acres), and ASRC owns or otherwise controls a little less than one-third of the area. Until the 2001 North Slope foothills sale, most of the state area had not been leased; however, large tracts were leased in the late 1950s and early 1960s by the federal government, before conveyance to the state. About 405,000 ha (about 1 million acres) was leased in the May 2001 state sale. Over the past 30 years, the ASRC has actively sought to have its lands explored, and it has assigned exclusive exploration rights to several companies.

About 40 wells have been drilled in this subprovince, including those drilled in the Kavik and Kemik gas fields, 8 of them on Native lands. Although the area is gas-prone, there has been no market for gas, and only one well has been drilled in the area in the past 20 years. With the possibility of a gas pipeline and the discovery of immature to early-mature oil-prone source rocks, interest in the area has increased.

Exploration and production operations require large quantities of gravel and water. The foothills belt has few lakes to supply water for ice roads or pads or for production and waste disposal. As a result, the extent to which ice will supersede gravel is unknown. Rivers could be the preferred water sources in some places. Produced water might be sufficient for most waste disposal and production needs. River gravel also is scarce, and it could be necessary to mine upland areas to supply gravel for production facilities and their associated airstrips and roads.

Existing exploration and development technologies would be used extensively to provide the infrastructure and gas pipeline system. Acquisition of seismic data is under way and will continue into the foreseeable future. A drilling rig is under contract to one leaseholder, and exploration drilling could begin soon. The foothills area is expected to be a major source of gas, and it is reasonable to expect at least five significant fields would be established. Gas development could be under way by the time a trans-Alaska gas pipeline is completed, and production could begin as early as 2010. Gas production should continue into the 2040s.

These gas fields will have small footprints, but the accompanying pipeline system could easily extend 161 km (100 mi) or more to the west from the pipeline. Much if not all of the gas pipeline system probably would be buried. Based on the size of surface geological features (exposed anticlines), an individual gas accumulation could have 10-15 TCFG. Technically recoverable reserves are expected to be at least 25 TCFG.

Oil production and economically recoverable reserves in the area are expected to be modest by North Slope standards and secondary in importance to gas. They would most probably be found in fields of 300 million to 400 million bbl of oil or less and be developed much later, possibly not until after 2020. Additions to oil reserves are expected to be about 1 billion bbl.

A recent paper, presented by Anadarko Petroleum (Nelson 2002), suggests that the foothills area technically recoverable reserves are 0.5 billion to 2.5 billion bbl of oil and 20-40 TCFG.

Beaufort Sea

The Beaufort Sea area consists of federal and state lands off shore from the seaward extension of the Alaska-Yukon Territory border west to a line extended north from Point

Barrow. The federal and state lands are administered through different leasing programs, and the distance from onshore facilities and the differences in water depth dictate that we address the two areas separately.

Federal Outer Continental Shelf

The federal OCS area lies seaward of the three-mile limit, or extensions of this limit, seaward of the offshore islands and bay mouths; the OCS is administered by the Minerals Management Service (MMS) of the Department of the Interior. Thirty exploration wells have been drilled on federal or joint federal-state leases. Eleven were deemed capable of production and five were termed significant discoveries by the MMS. Oil has been the focus of all exploration to date, but if a gas pipeline were built, gas could be the target of exploration and development.

It is probable that there will be a short-term decrease in exploration and consequently little development or production activity in the federal portion of the Beaufort Sea other than at Northstar. An exploration well could be drilled on the McCovey prospect during the 2003 drilling season. Leasing and drilling will be below historic levels for the next 10-15 years, perhaps until the early 2020s.

Individual ERR discoveries for oil can be anticipated to range from 100 million to 2 billion bbl. Northstar is at the lower end of that range. Prospects like McCovey and Kuvlum could reach or exceed a billion barrels. Individual gas fields could range from a few hundred-billion cubic feet to a few trillion cubic feet of gas. These finds could be oil-associated gas, as at Prudhoe Bay, or pure gas accumulations, as at the Barrow and Kavik gas fields. ERR additions of 2.5 billion bbl of oil and 15 TCFG are possible.

Over the long-term, activity could increase if nearby onshore and nearshore state lands are explored and developed. For example, if Point Thomson were developed, it might be more feasible to consider development of other discoveries in that area. The additional 15-20 years also will provide time to more fully research and implement technologies that would reduce the environmental consequences of Beaufort Sea exploration and production, especially under conditions of broken ice. By the second quarter of the twenty-first century, exploration could increase to levels seen in the middle 1980s and early 1990s. If new technologies were developed, the life of the facilities at Prudhoe Bay and other major fields would be prolonged, as would use of the trans-Alaska pipeline.

State Nearshore Lands

Leasing and exploration began in 1979 on state lands that lie within the three-mile limit. Significant discoveries have been made at Endicott, Niakuk, West Beach, Point McIntire, and Midnight Sun. The undeveloped Flaxman Island discovery lies just west of the mouth of the Canning River and offshore from Point Thomson. Exploration for oil has dominated the effort, but gas could be a target of future exploration and development.

The state Beaufort Sea lands are likely to continue to be desirable holdings, and leases will be retained and evaluated as promptly as circumstances and priorities permit. The likelihood of leasing significant new areas probably depends on the eventual availability of the deferred tracts lying offshore from the National Petroleum Reserve-Alaska and in the Arctic National Wildlife Refuge. The amount of activity should remain constant for the next 20-25 years and then gradually decline as the oil fields are depleted over the two to three decades thereafter. The gas fields will, in large part, be found later in the exploration cycle and would be brought to production more slowly. The life of the gas fields can be expected to extend beyond that of the oil fields. Over the next 25-30 years, exploration could add 1 billion bbl ERR of oil and modest amounts of natural gas (5-10 TCFG).

National Petroleum Reserve-Alaska

The National Petroleum Reserve-Alaska is administered by the Bureau of Land Management (BLM), with technical assistance in resource evaluation and lease sales management from the USGS and MMS, respectively. Before 1999, the only National Petroleum Reserve-Alaska lease sales were held in the early 1980s (BLM 1990). The impetus for the 1999 sale was the discovery of the Alpine oil field just to the east of National Petroleum Reserve-Alaska.

The Alpine discovery stimulated interest in the reserve, especially in the oil-prone northern Barrow Arch. However, the possible construction of a gas pipeline also has enhanced the prospects for the southern gas-prone area in the foothills of the Brooks Range. The Gubik gas discovery and several other smaller gas fields demonstrate the potential for gas in this southern area. A Department of the Interior report estimated that the National Petroleum Reserve-Alaska has undiscovered, technically recoverable reserves of 2.1 billion bbl of oil and 8.5 TCFG. A USGS report (Bird and Houseknecht 2002) lists the TRR volume of oil as 5.9 billion to 13.2 billion bbl, with a mean expected value of 9.3 billion bbl. The new estimate of gas potential is 40-85 TCFG, with a mean expected volume of 60 TCFG. That evaluation presents results for new data, new play concepts, and better seismic data; it offers a 3- to 6-fold increase in the TRR estimate.

Barrow Arch Trend

The northern portion of the National Petroleum Reserve-Alaska lies over the Barrow Arch, which trends westward across to Barrow. The Barrow Arch is parallel to subparallel to the coast and serves as a focusing mechanism for hydrocarbons that migrate out of the deep basins and as such favors the accumulation of oil and gas. The search for commercial quantities of oil has focused on this portion of the reserve.

The Barrow Arch trend—that portion of the reserve from the coast of the Beaufort Sea south to about 69° 45′ N latitude—could be an area of active exploration over the next 10-15 years. Despite restrictions on drilling and on placement of surface facilities, leasing is likely to be vigorous, as is drilling activity, which will be aided by new technologies and the use of three-dimensional seismic data. The potential exists for several moderate to large oil fields, in the size range of the Alpine field, and for numerous smaller satellite fields. Competition should increase, especially in those areas more remote from current infrastructure and production, where the established producers would have less advantage. None of the larger fields found in the post-2001 period is likely to be producing before 2008, because the time required to delineate the accumulation and build the necessary infrastructure is seasonally limited and earlier, more proximal discoveries would have priority. The larger fields can be expected to have a life of 20 years or more.

Gas discoveries would lag somewhat behind the oil fields in terms of investment and development. If built, a trans-Alaska gas pipeline probably would not be in operation before 2009, and the gas reserves at Prudhoe Bay would be the focus of any early development, followed by those at Point Thomson and perhaps by discoveries in the Brooks Range foothills because of their proximity to the pipeline. Gas fields in the northern portion of the reserve are not likely to be developed and put in production before 2020.

Exploration in the northern portion of the National Petroleum Reserve-Alaska could add 3 billion bbl to the North Slope's reserve base. The bulk of these reserve additions would occur over the next 10-15 years, but if gas is present in commercial quantities, its development will follow that of oil. A reasonable estimate for gas reserves is 5-10 TCFG. The 2002 resource evaluation (Bird and Houseknecht 2002) suggests that, for the northern portion of the reserve, the mean expected TRR for oil is 7.5 billion bbl and the mean expected TRR for gas is 20-25 TCFG.

The Alpine model, or refinements of it, would be used for exploration, development, and pipeline construction. Although the footprints would be small, even assuming advanced construction techniques and the uncertain ability to forgo a permanent gravel road for maintenance, pipelines to this area would greatly extend the web of aboveground structures. If commercial discoveries extend to the vicinity of Barrow, the pipeline system would extend more than 403 km (250 mi) from east to west, with spur lines 32 to 81 km (20 to 50 mi) long, trending north-south from the trunk lines. The system of pipeline and infrastructure in the newly developed areas would look much like the Alpine field does today, but the accumulation of fields would affect a larger area.

Brooks Range Foothills

The area from the latitude of Umiat and Gubik to the National Petroleum Reserve-Alaska's southern limits is thought to be predominantly a gas-prone province. Studies of the Umiat oil field indicate potential for additional relatively substantial oil accumulations, and the Gubik gas field and other smaller discoveries at Square Lake and Wolf Creek provide evidence of the potential for gas. All previous exploration in this area was for oil.

In the near term, the foothills region could be the least active area, producing less than even the Beaufort OCS. To achieve a large amount of activity, a series of events must occur in the other exploration subdivisions of northern Alaska. They include building a gas pipeline, establishing a reliable market and price for gas from the major gas fields of the northern portion of the Colville-Canning Province, discovering sufficient gas reserves in the Colville-Canning foothills to support a new infrastructure and pipeline system, and maintaining enough capacity in the pipeline system to support additional volume. If those conditions are met, exploration and development would proceed in the same general fashion as elsewhere on the North Slope.

An individual gas field in this region could have reserves of 5.0 TCFG or more, but the size of any oil fields is anticipated to be limited and not to exceed 200 million bbl, which could be too small for development as a standalone field. Currently available data are limited, but undiscovered gas reserves could be 15-20 TCFG. The 2002 USGS estimate (Bird and Houseknecht 2002) places a mean of 35-40 TCFG in the central and southern portions of the reserve.

Oil accumulations are expected to be small by North Slope standards; economically recoverable reserves are estimated between 500 million bbl and 1 billion bbl. In contrast, Bird and Houseknecht (2002) suggest that there is an expected mean TRR of 1.9 billion bbl in the southern portion of the reserve.

Any exploration and development would probably occur after activity in the other exploration subdivisions and probably not before 2015. The scale and style of operations would be similar to that at Alpine. Spills are not a concern with gas, but the extensive pipeline system that would be required to transport the gas to a trans-Alaska gas pipeline would be conspicuous if it were not buried.

Arctic National Wildlife Refuge—1002 Area

Whether Congress will open the area to oil and gas exploration is unknown, but it is useful to assess what might happen if it did. Of the Arctic National Wildlife Refuge's approximately 8 million ha (19 million acres) (Bird and Magoon 1987), the only part with potential for oil and gas exploration and development is the coastal plain 1002 Area of approximately 607,000 ha (1.5 million acres) (Bird and Magoon 1987).

The Kaktovik Inupiat Corporation, which controls the surface, and the ASRC, which controls the subsurface mineral rights, own an extensive in-holding in the north-central portion of the 1002 Area. This portion of the North Slope has long been considered to have great potential for oil and gas. It lies between the Prudhoe Bay area fields to the west and the numerous, but as yet uncommercial, discoveries in the Mackenzie delta area to the east in Canada. If the first federal lease sale were held in 2006, oil production could begin by 2013 and gas production by 2020. Estimates of the oil and gas potential of the 1002 Area vary.

The current USGS evaluation of the Arctic National Wildlife Refuge (Bird and Houseknecht 1998) assigns a mean TRR of 10.3 billion bbl for oil (conservatively, this is an ERR of 3.2 billion bbl) and 8.6 TCFG (no estimates of economically recoverable gas were made). Unpublished industry evaluations suggest that higher ERR volumes of oil and gas are possible. Exploitation of reserves of that size, if realized, would extend the productive life of the older fields.

PROJECTIONS OF DIRECT EFFECTS TO THE YEAR 2025: INFRASTRUCTURE ANALYSIS

The committee's projections of direct effects are based primarily on trends from the past 13 years (Figure 5-1). By 2025, the road network would expand by another 129 km (80 mi) if the growth rate is constant. This projection, however, could underestimate growth if long roads are built to Alpine or Barrow or are used to connect major new oil and gas fields in the Brooks Range Foothills or elsewhere. Based on the 1988-2001 rate of 17 ha (42 acres) per year, the total gravel-covered footprint would increase to about 4,150 ha (10,250 acres) by 2025, and the total area of direct effects (roads, pads, gravel mines) would increase to about 8,000 ha (18,700 acres). An additional 200 ha (500 acres) of gravel mines would be needed to build the roads and gravel pads. Advancing technology and the location and configuration of new oil and gas fields would affect the extent of roads and gravel-covered tundra. Development is likely to include more satellite fields on small gravel pads, similar to those at Endicott and Alpine. They could have airstrips and small road systems disconnected from the main road network. Other gravel roads in the area are being considered by the Alaska Department of Transportation and the North Slope Borough (Petroleum News Alaska 2002), including a 170-km (106-mi) gravel road south from Nuiqsut that would connect to the Dalton Highway near Pump Station 2 (Alaska DOT 2002). More ice roads will reduce the need for gravel roads, although ice roads might not be practical in areas with few lakes, such as the Arctic Foothills; areas with little gravel, such as parts of the

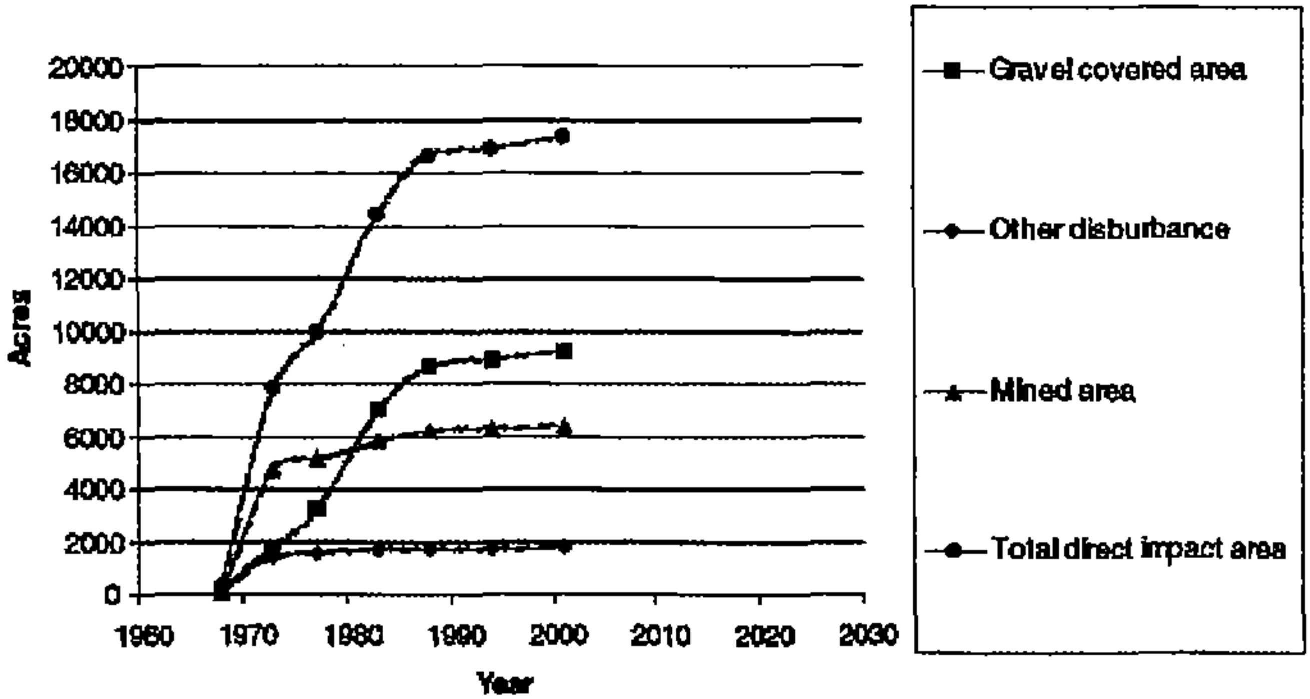


FIGURE 5-1. Direct effects of early exploratory trails and peat roads are shown with diamonds; gravel mines with triangles; gravel covered areas including roads, airstrips and pads with squares; and total area of direct effects with circles. Dalton Highway is not included. Source: Alaska Geobotany Center, University of Alaska Fairbanks 2002.

National Petroleum Reserve-Alaska, or areas that are distant from existing roads. The effects of these roads would accumulate with those of any other roads that might be built for other purposes. For example, the Trans Alaska Pipeline and the haul road, completed in 1974, covered approximately 4,050 ha (10,000 acres) on the North Slope (Pamplin 1979). It also is possible that the projections are an underestimate if major support facilities, new causeways, long roads, or airstrips are needed or if ice roads and pads cannot be used. Fewer roads might require more aircraft traffic; insufficient information is available for quantitative analysis of how any such effects might accumulate.

CLIMATE CHANGE AND OTHER INFLUENCES ON FUTURE OIL AND GAS DEVELOPMENT

The scenario on which we base our projections assumes that climate change will not seriously affect oil and gas activities on the North Slope. However, as a result of global emissions of greenhouse gases, Earth's mean surface temperature is expected to rise by 1-3.5 °C (1.8 to 6.3 °F) over the next century, and changes in Arctic Alaska are expected to be even greater (Houghton et al. 1995, 1996). The two principal climate models used in assessments (the Canadian and Hadly Center models) correctly reproduce the observed late-twentieth-century warming, and they predict continued warming throughout Alaska of 4-10 °C (7.2-18 °F), and 3-6.5 °C (5.4-11.7 °F) respectively, during the twenty-first century (Alaska Regional Assessment Group 1999). The strongest warming is expected in the north, so a plausible (though quite uncertain [Serreze et al. 1999]) twenty-first century warming prediction for the North Slope might be 5-10 °C (9-18 °F), or 0.5-1 °C (0.9-1.8 °F) per decade. This exceeds the estimate for mean global warming by a factor of 3 or so. The Arctic amplification is attributed, at least in part, to "ice-albedo feedback": As the reflective areas of arctic ice and snow retreat, the earth absorbs more heat, accentuating the warming (Chapman and Walsh 1993, NAST 2001).

Other predictions are that most of the North Slope warming will occur in the winter, and that precipitation and evaporation will increase. The predictions and models are supported by the experience of Alaska Natives, who have reported changes in the amount of ice cover and reduced effectiveness of ice cellars. Some warming has already occurred. The onset of the off-road tundra season is about 70 days later than it was in the early 1970s (Chapter 7); springtime warming has led to earlier snowmelt and emergence of vegetation (Griffith et al. 2002). Additional warming could reduce the usefulness of ice roads and pads or of some off-road technologies.

Projected Changes in the Arctic Marine Environment

Ice cover in the Arctic Ocean has been shrinking by about 3% per decade over the past 20 years (Johannessen et al. 1999). The loss of volume could be even greater than that, because Arctic sea ice has been thinning by as much as 15% per decade (Rothrock et al. 1999), from an average thickness of 3.1 m (10.2 ft) in the 1950s to an average of 1.8 m (5.9 ft) today (Weller 2001).

If the trend were to continue, within 50 years the sea ice could disappear entirely in summer (see map, page 18, *NOAA Report of the National Coastal Assessment Group*, October

2000). Even if changes are less dramatic, the amount and duration of open water near the north coast of Alaska is likely to increase substantially. This is significant because ice edges are highly productive regions where interactions between physical and biologic processes result in substantial phytoplankton blooms. Those blooms in turn support populations of zooplankton and arctic cod (*Boreogadus saida*) and their predators (Niebauer 1991, Wheeler et al. 1996). The migrations of belugas (*Delphinapterus leucas)*, narwhals (*Monodon monoceros*), and harp seals (*Phoca groenlandica*) to ice-edge regions are associated with bursts in productivity and the subsequent abundance of arctic cod in those areas during the summer plankton blooms.

The loss of sea ice also would reduce critical habitat for marine mammals and seabirds that use ice shelves and flows as platforms for feeding, resting, reproducing, and molting. Ringed seals (*Phoca hispida)* depend on stable, fast ice for raising their young. They and polar bears (*Ursus maritimus)* are the only marine mammals that regularly occupy land-fast Arctic ice (Tynan and DeMaster 1997). The species that use and depend on sea ice would not necessarily decrease in overall abundance, because new habitats are likely to become available farther to the north. However, if migrations of bowhead whales (*Balaena mysticetus*), for example, were to shift farther offshore and if populations of seals near the coast were to be seriously reduced, the consequences for coastal human subsistence cultures could be dramatic. In addition, increases in the amount and duration of open water could make the usually unnavigable Northwest Passage available for ocean transport. Already in 1999, Russian companies sent two large drydocks to the Bahamas through the Northwest Passage. Oil companies might have improved opportunities for drilling off the coast. The U.S. Navy is assessing the implications of the continuing reduction of sea ice for the scope of its operations in the Arctic Ocean (ONR 2001). The addition of new sea traffic in the Northwest and Northeast passages could lead to new environmental effects, caused by spills, noise, or collisions, for example, that could accumulate with effects of oil and gas development.

Projected Changes in Terrestrial and Freshwater Environments

Changes in tundra will result from the direct and the indirect effects of climate change and its drivers. No direct effects on animals from increased CO_2 concentrations are anticipated, but direct effects on plants (photosynthetic and respiration rates) would be expected. In addition, there will be direct and indirect effects of temperature changes on plants, animals, and microorganisms. Predicting the effects of warming on tundra ecosystems is difficult because of the complexity of the ecosystem. In addition, the time scales at which different consequences appear are highly variable: some processes begin within a day, others will not become fully apparent for centuries.

Few studies have yet been conducted on flat, coastal, polygon-sorted tundra, but the International Tundra Experiment system is using passively warmed, open-top chambers in 26 arctic and alpine tundras to compare the effects of warming on plant growth and flowering (Henry and Molau 1997, Arft et al. 1999). Investigators at Toolik Lake on the north slope of the Brooks Range have shown experimentally that decomposition and mineralization of nitrogen in tundra is strongly limited by low soil temperatures and high soil moisture (Nadelhoffer et al. 1992). Thus, with increased turnover of soil organic matter because of increased warming, a high potential exists for redistribution of nitrogen from soils (with low C:N ratio) to vegetation (with high C:N ratio), but accompanied by little or no net change in ecosystem stocks of nitrogen (Shaver et al. 1992).

If warming were accompanied by decreased soil moisture, large increases in respiration would be expected to cause long-term loss of both carbon and nitrogen from the system. In addition, the increased depth of permafrost thaw of would lead to increased losses of mineralized nitrogen because of drainage. If so, increases in nitrogen uptake and net primary production (NPP) in Phase II would be insufficient to compensate for nitrogen and carbon losses attributable to leaching and respiration. Therefore, even though the ecosystem eventually would return to equilibrium—NPP equals respiration (that is, there is no accumulation of biomass through carbon storage) (Vourlitis and Oechel 1997, 1999; Waelbroeck et al. 1997)—over 50-100 years there would be a net loss of carbon to the atmosphere. Increases in CO_2 concentrations also would result in changes in allocation of carbon and nitrogen among plant tissues, which would affect the palatability of those tissues to herbivores and potentially alter the dynamics of herbivore populations. Warmer temperatures could favor the spread of woody plants over portions of the North Slope and increase insect abundance and periods of activity.

Although the depth of the active layer is likely to increase in a warmer climate, the general pattern of stream flows is unlikely to change much. Increased snowfall, which is possible, would result in greater spring runoff, and warmer winters should reduce the depth to which lakes and streams freeze, thereby altering wintering habitat for fish and other freshwater animals.

Changing Climate and Permafrost

As mean air temperatures rise in a warming climate, the earth's surface generally warms by an amount that varies locally with vegetation, moisture, snow, and other conditions. This surface warming propagates slowly downward into permafrost, typically taking about a century to reach a depth of 100 m (300 ft). Although little direct information is available on the North Slope climate and its 100-year history, temperature measurements in deep wells across the North Slope show that near-surface permafrost temperatures, though variable, typically increased by 2-4 °C (3.6-7.2 °F) in the 20^{th} century before the 1980s (Lachenbruch and Marshall 1986) and that additional rapid changes have occurred since (e.g., Clow and Urban 2002). These results are roughly consistent with the large changes seen in broadly averaged twentieth-century arctic air temperatures (Hanson and Lebedeff 1987, Chapman and Walsh 1993, Hansen et al. 1999, Lachenbruch et al. 1988). Although the early twentieth century warming might include unrelated natural effects (Stott et al. 2000), rapid changes of the past few decades are consistent with anthropogenically driven climate models that predict continued rapid warming in the twenty-first century (Alaska Regional Assessment Group 1999). As the permafrost warms, its ability to support engineering structures diminishes, so it is necessary to consider how much additional warming is likely and how that might influence future effects of oil and gas development.

Permafrost Conditions

The mean annual surface air temperature over much of the North Slope is -12.5 °C to -9 °C (10-16 °F) (Haugen 1982, Zang et al. 1996, Olsson et al. 2002). The corresponding near-surface permafrost temperature is locally variable and typically 2-5 °C (3.6-9 °F) higher (e.g., Brewer 1958a). The difference is caused by winter snow cover and complex processes in the active layer. This is generally cold "continuous permafrost" (no gaps) defined by its temperature (beneath the 20-meter layer subject to seasonal change) below -5 °C (23 °F) (Lunardini 1981). Continuous permafrost is robust in the sense that its temperature could be raised several degrees before destructive thawing would begin. By contrast, spatially discontinuous permafrost (with gaps) with near-surface temperatures near 0 °C (32 °F) is fragile and more easily disrupted by warming.

Throughout the coastal plain and most of the foothills, measured temperatures near the surface in permafrost are so low—typically -10 °C to -6 °C (14-21 °F) (Lachenbruch et al. 1982b, Osterkamp 1988)—that they could withstand several decades of warming at the predicted rate before they start the mechanically troublesome transition from continuous to discontinuous permafrost. As the climate warms, the natural permafrost temperatures rise, leaving a smaller margin for engineering disturbance. The effects of persistent climate warming could eventually involve failure of neglected structures, or the requirement to modify design, or in some cases, to completely abandon some design options or practices. For example, thicker gravel would be required to preserve permafrost as warming proceeds. Abandoned work pads and roads will become unusable as they are cut up by deep polygonal troughs over thawing ice wedges or by other thermokarst degradation. After some degree of warming, preserving ice-rich permafrost with gravel will become unworkable well before the permafrost approaches the discontinuous state near 0 °C (Lachenbruch 1959, Heuer et al. 1985).

Because most of the predicted warming would occur in winter, the period during which nondestructive surface travel can take place over a frozen active layer that is protected by snow cover or ice roads would be shorter, decreasing the capacity for winter operations.

Interaction with Climate

It is generally assumed that as the mean temperature of permafrost rises, the active layer that thaws each season will thicken. However, where moisture and organic material increase the active layer might actually thin as the climate warms (Lachenbruch 2001). More generally, the change in the physical state, and the associated biotic changes, of the active layer with changing climate are difficult to predict with current information.

The difficulty of predicting the effects of changing climate on permafrost and, ultimately, of predicting how effects of oil and gas development might accumulate, involves much more than uncertainty in predicting climate change. We know that the cold deep permafrost that dominates ecosystems and constrains landuse on the North Slope is a consequence of low air temperatures, but we know little about the local distribution of those temperatures or other relevant climate parameters, now or in the past. (The topographically diverse North Slope, with an area of 20 million ha [50 million acres] has two U.S. National Weather Service stations, both on the Arctic coast.) When the climate changes, effects are transmitted to permafrost through poorly understood processes, physical and biological, that operate in the active layer, whose new state becomes difficult to predict. By contrast, once a change in mean temperature penetrates the active layer (and establishes the temperature at the top of permafrost) it propagates downward into permafrost predictably according to simple physical rules of heat conduction. The shape of the temperature-depth profile to 200 m (660 ft) contains a faithfully preserved, if somewhat ambiguous history of permafrost surface temperature changes over the past century or more (Clow 1992, Lachenbruch 1994).

The needed understanding of the connection between climate, active layer, and permafrost requires repeated measurements in the same place of surface heat balance, snow depth, and temperatures through the active layer to permafrost (a few meters). This could be done with remote self-contained instrument stations (now available at modest cost) distributed over the North Slope or other areas of concern (e.g., Olsson et al. 2002, Clow and Urban 2002). Insights into the history of temperature at the top of permafrost (the bottom of the active layer) and its rates of change can be obtained from careful down-hole thermal measurements in wells at any location in the continuous permafrost.

Permafrost and the Encroaching Sea

The steep permafrost bluffs behind the narrow beaches of the Beaufort and Chukchi seas are receding an average of 2.5 m (8 ft) per year; this is the most rapidly retreating shoreline in the United States (Reimnitz et al. 1985). The bluffs have been retreating rapidly for thousands of years because of the destructive thermal effects of the surf, which thaws and undermines the bluffs and carries away the debris (MacCarthy 1953). (The retreat can be expected to accelerate with warming climate and diminishing sea ice.) The retreat poses some engineering problems for pipelines and other facilities that cross the shoreline, and it presents a potential risk from toxic-waste pits abandoned by "freezeback" during earlier coastal exploratory drilling. But most important, the marine encroachment controls the temperature and distribution of permafrost beneath the edge of the sea.

As the shoreline migrates inland, a coastal point on the North Slope undergoes a dramatic climate change—its mean temperature increases from about -11 °C (12 °F), characteristic of land, to -1 °C (30 °F), characteristic of the seabed (Lachenbruch 1957a). This transition occurs over a band of a few kilometers where the water is less than 2 m (6.5 ft) deep and where grounded sea ice cools the seabed in winter (Lachenbruch and Marshall 1977, Osterkamp and Harrison 1982). Over this short distance we pass from robust permafrost with a large subfreezing cold reserve on shore to the more fragile subsea condition where temperatures are close to melting throughout—a condition that is characteristic of discontinuous permafrost 500 km (300 mi) to the south. In fact, the ice-bonded state of the subsea permafrost is likely to be discontinuous because of local variations in salinity (and hence in freezing temperature) of the water (Harrison and Osterkamp 1978, Nixon 1986).

The 600 m (2,000 ft) deep, cold, ice-rich permafrost at Prudhoe Bay would warm to near-melting temperatures from top to bottom about 2,000 years after inundation, but its ice-rich condition could persist down to hundreds of meters (60 km [38 mi] from shore at current transgression rates) for another 25,000 years (Lachenbruch 2001, figure 5; Lachenbruch et al. 1982a; Nixon 1986).

The importance of the retreating permafrost shoreline for human activities is that the shoreline provides a sharp separation between cold permafrost on shore and a warm, near-melting permafrost offshore that is potentially more vulnerable to engineering disturbance. The remarkably rapid retreat yields a transient condition that permits deep, ice-rich (but warm) permafrost to persist to tens of kilometers off shore. Diminishing sea-ice cover from climate warming might further increase seabed temperatures, slowly decreasing the cold reserve of any shallow permafrost there. This is a zone of active exploration and development, including the Northstar project and now-suspended Liberty project. It provides support for artificial islands, causeways, buried pipelines, drill pads, and other infrastructure.

OTHER MINERAL RESOURCES

The scenario used by the committee to predict the accumulation of effects is confined to exploration for and extraction of oil and gas. However, the North Slope contains significant deposits of other hydrocarbons, especially coal and coalbed methane. If those deposits were exploited in the near future, the committee's scenarios could change dramatically. Because of economic and other uncertainties, the committee cannot predict the degree to which any of these sources will be exploited or when such exploration might occur.

Coal

The coal-bearing beds on the North Slope of Alaska, mainly in rock sequences of the Nanushuk Group of Cretaceous age, are well exposed in the western part of the National Petroleum Reserve-Alaska in bluffs along the Kokolik, Kukpowruk, Utukok, Kuk, Meade, and Colville rivers and have been penetrated in several of the test wells drilled in the northern foothills (Figure 5-2). They range in rank from lignite A to high-volatile A bituminous and are low in ash and sulfur (Sable and Stricker 1987). Sable and Stricker (1987) estimated the amount of Cretaceous coal on the North Slope at 1.3 trillion metric tons (t) (1.7 trillion short tons of bituminous coal).

East of the Colville River, coal beds of lesser potential and rank are exposed in sequences of the Sagvanirktok formation of Tertiary age and extend off shore (Sable and Stricker 1987). Those coal beds rank from lignite A to sub-bituminous B with a mean of sub-bituminous C with low sulfur and variable ash content (Roberts et al. 1991). Stricker (USGS, personal communication, 2002) estimates the total hypothetical volume of the Tertiary coals on the North Slope and offshore Beaufort Sea at 608 billion t.

Coals of lower Mississippian age are exposed at Cape Lisburne, in the eastern Brooks Range, and in wells south of Barrow (Sable and Stricker 1987, Wahrhaftig 1994). They rank from low-volatile bituminous to anthracite and are low in sulfur and ash (Tailleur 1965, Conwell and Triplehorn 1976). Merritt and Hawley (1986) listed the coal volume at Cape Lisburne as 842 million t.

Coal was mined on the North Slope at Cape Beaufort to provide fuel for commercial whaling ships as early as 1879 (Schrader and Peters 1904). Alaska Natives have mined coal in the Corwin Bluffs and in the lower Kuk and the Meade rivers, off and on for many years, but they currently rely mainly on natural gas and diesel oil for generating heat and electricity. Various mining companies have sampled and made preliminary investigations into the feasibility

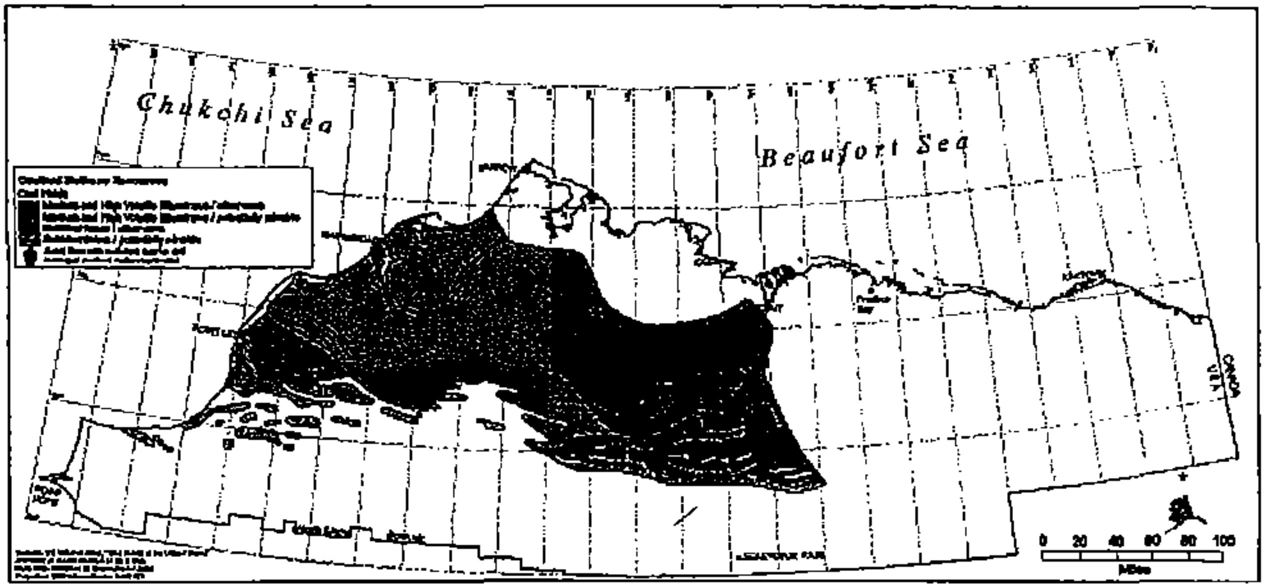


FIGURE 5-2. Coal and Coalbed Methane Resources on the North Slope. Drawing by Mapmakers Alaska 2002.

of commercial mining of coal for export. The ASRC has recently considered such an operation in the western North Slope.

One problem for commercial mining of coal from the western North Slope involves transportation. There are few roads and there is no year-round seaport. The nearest seaport with docking facilities is at Kivalina, about 320 km (200 mi) by air from the best Cretaceous coal exposures. The Kivalina seaport was built for the export of lead and zinc ore concentrates: It is open for shipping about 100 days each year. Ore concentrates must be shipped on barges about 6 km (4 mi) out to sea where ore ships can be anchored and loaded.

A recently built 84 km (52 mi) road in the De Long Mountains runs from the Red Dog lead and zinc mine to Kivalina (Skok 1991). A connecting road to a North Slope coal mine could be built to haul coal to Kivalina, but additional storage facilities would be needed at Kivalina. Construction of a new seaport at Oumalik Lagoon or Kotzebue and access roads have been suggested for shipping coal from the North Slope (Fechner 1991). However, large-scale coal mining under arctic conditions, and hauling overland to Kivalina or to a new seaport with dock facilities, probably is not economically feasible in light of competition from existing lower-cost coal operations in Cook Inlet and elsewhere in the United States. The only commercial mining of coal in Alaska, for export to Korea, is from the Usibelli Coal Mine at Healy on the Alaska Railroad, which hauls the coal to a year-round seaport and to loading facilities at Seward.

Intermittent coal mining for local use probably will continue unless some other local fuel source, such as natural gas or coalbed methane, is developed for use in small communities in the North Slope and elsewhere in Alaska.

Perhaps some innovative engineering plan, such as transporting coal as a slurry in a pipeline to tidewater, or burning coal in place to generate and transport electrical power to market through power lines or by other means, could eventually become economically feasible. However, unless subsidized, substantial coal mining on the North Slope in the near future is unlikely.

Coalbed Methane

The coalbed methane (CBM) potential of the North Slope is estimated to exceed 800 trillion cubic feet (tcf), and could exceed the resources of the contiguous states, approximately 695 tcf. It is estimated that there are 150 significant coal seams, ranging from 2 to 9 m (5 to 28 ft) thick, in the western Colville Basin (Clough et al. 2000). The growth of CBM production in the contiguous states and a new state program in Alaska has spurred interest in developing these resources. The Alaska Division of Geological and Geophysical Surveys (ADGGS) began a program in 1999 to encourage noncompetitive exploration and development by industry of shallow (within 910 m [3,000 ft] of the surface) reservoirs of natural gas, including CBM (Clough et al. 2000). About 25 Alaska communities are atop or adjacent to potential CBM beds. The state, in cooperation with Alaska Native corporations, has set up a demonstration project at three locations, Fort Yukon, Chignik, and Wainwright (Dolan 2001). The ADGGS, USGS, and the ASNC are cooperating on a study program that includes drilling to collect subsurface data on the geohydrology and potentially recoverable amounts of CBM.

Gas Hydrate

Natural gas is expected to be more important in the near term for power generation and transportation because of the general effort to reduce air emissions and the expected decline in liquid oil resources. Methane gas hydrate is a potentially enormous natural gas resource that is hundreds of times greater than the estimated conventional U.S. natural-gas resource base (DOE 1999). Gas hydrate is a solid, icelike material that contains molecules of gas bound in a lattice of water molecules. On decomposition, a gas hydrate solid can produce as much as 160 times its volume of gas. Gas hydrate occurs in the deep-water regions of the oceans and in permafrost regions where temperature and pressure conditions are favorable for its formation and stability. Worldwide estimates of methane in gas hydrate are 700,000 tcf, and U.S. domestic resources are estimated between 100,000 and 300,000 tcf (Kvenvolden 1993, Collett 1995). In the 1980s, extensive research and resource estimation programs were funded by the U.S. Department of Energy (DOE), and recent interest in the feasibility of gas hydrate as a fuel has resulted in the National Methane Hydrate Multi-Year R&D Program (DOE 1999). Major gas hydrate deposits are associated with permafrost regions of Alaska, including those in the North Slope.

Many challenges remain before gas hydrate could become a producible methane resource, including characterizing its quantity, quality, and location; delineating the safety and environmental consequences of various production methods; and determining the economics of production (DOE 1999). The goals of the DOE program include removal of technological barriers to resource extraction by 2010 and development of guidelines for commercial production by 2015. The onshore Arctic is an initial target area for feasibility studies because of the existing infrastructure and the large estimated volume of gas hydrate in that area. Even optimistic estimates suggest that gas hydrate will not become a significant source of methane for 10-20 years, and more conservative estimates place routine gas hydrate production as late as 2030-2060 because of technical difficulties and economic impediments (Milkov and Sassen 2001). Based on these considerations, the committee's scenarios do not include gas hydrate as a viable component of natural gas production on the North Slope. Although the economic and technology barriers could be overcome, the first choice will be existing conventional natural gas deposits already characterized and, in many cases, already being produced but not exported.

Base Metal Deposits

The North Slope region contains potentially important base metal deposits. For example, the Red Dog lead and zinc mine is on the western end of a mineralized belt that extends east through the southern part of the National Petroleum Reserve-Alaska and through the Brooks Range, mainly south of the drainage divide, in the Wulik River drainage near the village of Kivalina. The area has been explored and studied by the BLM, USGS, and ADGGS. Excellent prospects for lead and zinc deposits have been found.

The indicated and inferred original reserves at the main deposit at Red Dog were calculated at 77.1 million t, averaging 17.1% zinc; about 13.2 t, averaging 5% lead; and 2.5 troy oz of silver per short ton (85.7 g of silver per metric ton) of ore. Cadmium and germanium are associated with the silver (Skok 1991). The estimates of the reserves are expected to increase as drilling around the main deposit continues. The main ore body is exposed at the surface and is about 1,300 m (4,400 ft) long; it varies from a few hundred meters to 430 m (1,400 ft) wide and averages about 30 m (100 ft) thick, with a thicker zone near the center of140 m (460 ft). Drill hole 26, near the center, intersected 140 m (460 ft) of ore, grading 29% zinc, 8% lead, and 140 g of silver per metric ton. The Red Dog is the second largest zinc deposit in the world, but probably the richest.

A second deposit, the Hilltop deposit, is located just south of the Red Dog main deposit and is of similar origin and geologic setting. The Hilltop contains copper sulfides, up to 3% copper in some samples, and 1 gram of gold per metric ton. It is estimated to contain several million tons of ore at grades comparable to those in the main deposit (Kulas 1992).

The Red Dog mine is a small open-pit operation. The ultimate pit depth will be about 150 m (500 ft) below the creek bed (Kral and Steve 1992). About 2.27 million t (2.5 million short tons) of overburden and waste were removed during mine development and used for road building and other facilities. About 1.8 million t (2 million short tons) of ore are blasted and removed from the open pit each year (about 6,000 short tons or 5,400 t each day, 365 days per year). The ore is milled on site and concentrates moved to Kivalina port on specially designed 75-ton trucks over a 84 km (52 mi) road. There the concentrates are loaded onto barges and towed to larger ore ships about 7 km (4 mi) offshore. Approximately 15 ships of 25,000 to 75,000 tons (70,000 to 210,000 m^3 internal capacity) call at the port each year during the 100-day shipping season (Cominco 1990). The mine (and related facilities) cost $450 million to develop and is expected to produce for 50 years.

6

Effects on the Physical Environment

Extraction of oil and gas from subsurface deposits involves deliberate alterations of the surface and subsurface physical environments, which in turn affect organisms living on the North Slope. This chapter focuses on the effects of industrial activities on the physical environment.

Most of the effects on organisms that are caused by changes in the physical environment are dealt with in chapters 7, 8, and 9, but some of those effects are mentioned here as well. For example, small areas of vegetation have been contaminated by spills of oil, other petroleum products, and saltwater, and road dust; vegetation has also been damaged by bulldozers, offroad vehicles, and ice roads; and destroyed where it underlies gravel pads and roads, or where it has been removed to make way for gravel mines (Forbes et al. 2001, Jorgenson and Joyce 1994, McKendrick 2000, Walker 1996). Alterations in vegetation can affect other organisms on the North Slope. Physical disturbances can affect fish migrations, the movements of caribou, and—in the marine environment—migration and distribution of animals, especially bowhead whales and fish. Oil-field activities can affect the number and distribution of predators, which can in turn affect the number and distribution of birds and some mammals.

PERMAFROST

The climate of Alaska's North Slope is much colder than that of other U.S. oil fields. As a consequence, the ground is permanently frozen to great depths (about 200-650 m, or 660-2,130 ft) (Lachenbruch et al. 1982a,b). In this permafrost zone natural processes are significantly different from those in unfrozen sediments, and this imposes a wide range of unique constraints on the development of industrial infrastructure and on the preservation of functioning ecosystems (Lachenbruch 2001).

A shallow surface layer, the active layer, thaws in summer to become an extensive wetland. Even though the climate is arid the meltwater cannot filter downward through the underlying impervious permafrost. The active layer contains and sustains the living tundra vegetation mat, which in turn sustains the region's diverse populations of land animals and influences landform processes like runoff, erosion, and soil flowage. Below the active layer, the permafrost generally contains a substantial fraction of ice. The integrity of the surface and any buildings, roads, or pipelines placed on it depends on the strength of that ice for support. Structures can topple or collapse if they upset the heat balance and thicken the active layer. Thus, changes in the thermal condition of the surface in permafrost terrain can have widespread effects that accumulate throughout the physical, biotic, and human systems.

Many of the physical effects of oil and gas development enumerated in Chapter 4 (from gravel roads, heated structures, offroad traffic, oil spills, gravel mining, oil wells, pipelines) can trigger environmentally significant changes in the physical behavior of the permafrost and the active layer. The ultimate environmental effects of such development cannot generally be anticipated without knowledge of the intermediate functioning of permafrost. For example, road dust can cause deep pools on the tundra surface by collecting solar radiation and thawing the underlying permafrost.

The general pattern of the committee's efforts has been to identify effects of the industrial activities described in Chapter 4 on the environment (described in Chapter 3). For permafrost, however, it is important also to consider reciprocal effects of the natural environment on development.

In fact, the most conspicuous physical effect on development could be the effect of permafrost on the industrial infrastructure itself. Structures must be designed to avoid thawing their own foundations. Dealing with this condition establishes the engineering configuration, or architecture, of North Slope oil development, which consists of a conspicuous network of 954 km (596 mi) of roadways elevated on thick gravel berms, and 725 km (450 mi) of pipeline clusters elevated on pilings (Table 4-2). They join more than 2,354 ha (5,817 acres) of thick gravel work pads above which are large heated buildings elevated on pilings, and, more recently, closely spaced oil wells that are cooled by extensive refrigeration equipment to preserve the superficial permafrost remnant that supports them. Some effects of this unique assemblage of thick gravel and associated permafrost-resistant infrastructure are discussed in chapters 7 (plants), 8 (animals), and 9 (people).

To understand the importance of permafrost in the evolution of the oil and gas infrastructure and the effects of physical development on the North Slope environment, it is useful to examine the controlling thermal processes. In this section we discuss natural and artificial processes relevant to oil and gas development. Most are mentioned again in later chapters in connection with specific effects.

Active Layer

The active layer that thaws each summer lies between the top of permafrost and the ground surface. It controls the influence of permafrost on surface processes and the influence of human activity on permafrost. The permanently frozen base of the active layer is impermeable to water and impenetrable to roots. Consequently, the active layer is the growth medium for surface plant communities; the reservoir for their water and nutrient supply; the locus of most terrestrial hydrologic activity; and a boundary layer through which heat, moisture, and gases are transferred between permafrost and atmosphere. The active layer protects the permafrost from summer warmth. Its thickness is a measure of the ground's ability to transmit heat. The active layer varies from as little as 20 cm (8 in.) in some areas of peat or poorly drained sphagnum moss to more than 2 m (80 in.) at some well-drained inland gravel sites. The thickness varies with the active layer's properties as well as with the locally variable thermal properties of the permafrost it protects (Lachenbruch 1959).

Disturbance to the surface, whether anthropogenic or natural, can affect the thickness and mechanical nature of the active layer and ultimately the composition of its plant communities. Such disturbances might include disruption of peat and living vegetation, changes in radiation properties, or alterations in the abundance of water. Disturbances can be initiated by off-road vehicular traffic, removal of vegetation, addition of gravel, paving, oil spills, and saltwater spills, deposition of airborne dust, or the modification of surface drainage (Chapter 7).

Ice-Wedge Polygons and Thermokarst

Typically, permafrost is cemented by ice that, in the upper few meters at least, occupies more space than the water-filled pores that would remain after thawing. Melting of such ice-rich or thaw-unstable permafrost results in thaw settlement and disruption of the surface and whatever is on it. The ice in permafrost, or ground ice, can be mainly in the pore space or it can be in large segregated masses. Ice content varies greatly from one North Slope location to another and so consequently does the potential for thaw settlement. Ice content increases sharply from Prudhoe Bay to Alpine on the Colville delta (Hazen 1999) and between many locations on the Arctic Coastal Plain and in the Brooks Range foothills.

The most troublesome disturbances are those for which a thickening of the active layer is not self-arresting; that is the thawed increment from permafrost flows off as a slurry rather than remaining in place to augment the active layer's insulation. This unstable process, called thermokarst, can lead to deepening pits and trenches, retreating scarps, and mud flows (Lawson 1982). It occurs commonly on the North Slope where the active layer is disturbed over ice-wedge polygons—widespread patterns of troughs shaped like giant mud cracks omnipresent on the coastal plain and much of the foothills (Figure 6-1). Below each trough is a wedge of almost pure ice a meter (3.3 ft) or more wide and several meters deep (Figures 6-2 and 6-3). The wedges form over centuries in recurring contraction cracks, opening during the winter and filling with ice each spring by downward percolation and refreezing of melted snow (Lachenbruch 1962). A roadway, heated building, or pipeline that thaws the underlying permafrost will soon be unsupported in a free span across the melting ice wedges. This thermokarst condition is illustrated by early roads on the North Slope that consisted of gravel laid 1 m (3.3 ft) thick on the tundra (Figure 6-4). Because the natural active layer in North Slope gravels is about 2 m (6.5 ft), the roads soon became impassable, even to foot travel. Compression by the gravel destroyed the insulating capacity of the organic mat, and the too-thin gravel disappeared into a network of deepening trenches left by thawing ice wedges (Ferrians et al. 1969, Lachenbruch 1966).

Heated Buildings

On the North Slope the typical result of a heated building constructed on the ground surface is a surface patch the shape of the foundation maintained at a temperature 25 °C (45 °F) or so above the ambient mean temperature of approximately -10 °C (14 °F). The shape of the thawed basin that grows in the permafrost under a building depends on these two temperatures, the width of the building, and its age, and it is easily estimated (Lachenbruch 1957b). Substantial thawing can develop quickly, leading to destructive thaw settlement, a fact well known to Alaskan cabin dwellers. This process leads to a conspicuous constraint on North Slope development—heated structures, even very large ones, generally must be elevated above the surface to let the cool air circulate below. The load that can be carried by their pilings depends on the temperature of the enclosing permafrost. If necessary, building design could be revised to accommodate a warming climate by refrigeration with thermo-siphons (e.g., Kinney et al. 1983) like those used to maintain the mechanical integrity of closely spaced oil wells. Where heated

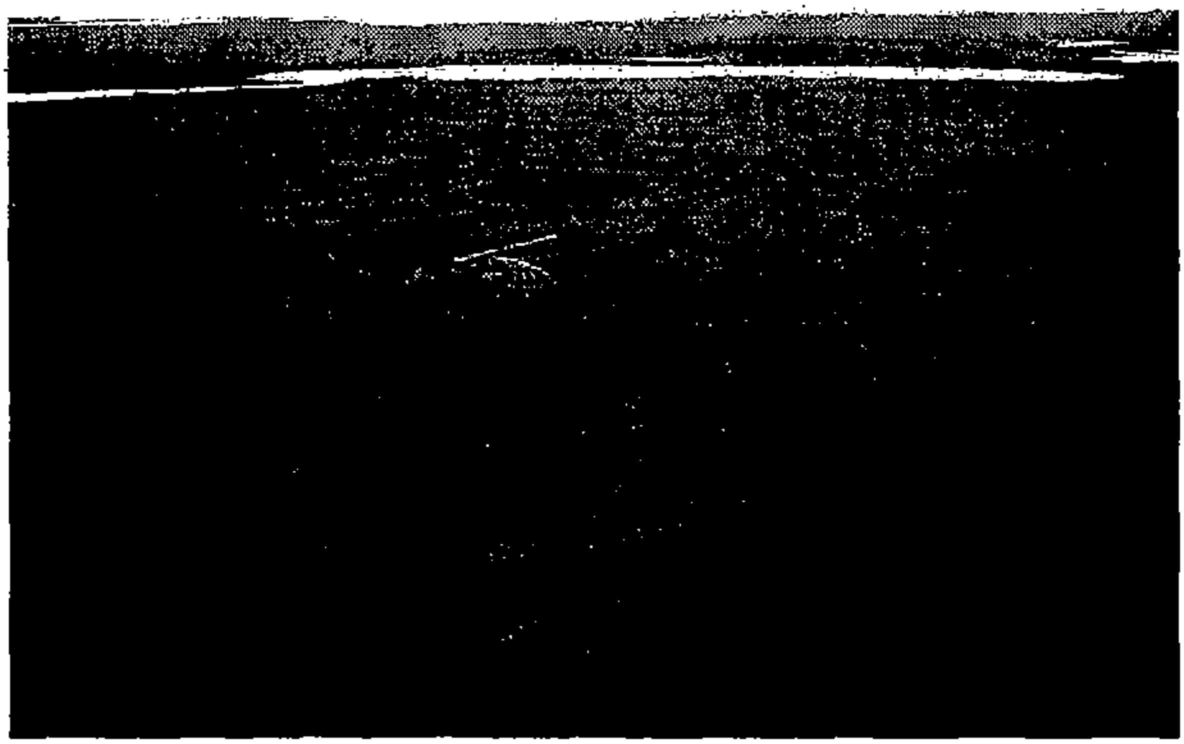


FIGURE 6-1. Ice-wedge polygons on the Arctic Coastal Plain; troughs are underlain by ice wedges. Peripheral ridges represent material displaced from permafrost by ice-wedge growth. Photo taken by George Gryc.

FIGURE 6-2. Intersection of three small ice-wedges exposed in an undercut bank of Elson Lagoon, near Barrow. Photo taken by Gordon Greene.

FIGURE 6-3. Upper portion of an ice-wedge exposed in a riverbank on the Colville Delta near Nuiqsut, Arctic coastal plain. Photo taken by H. J. Walker.

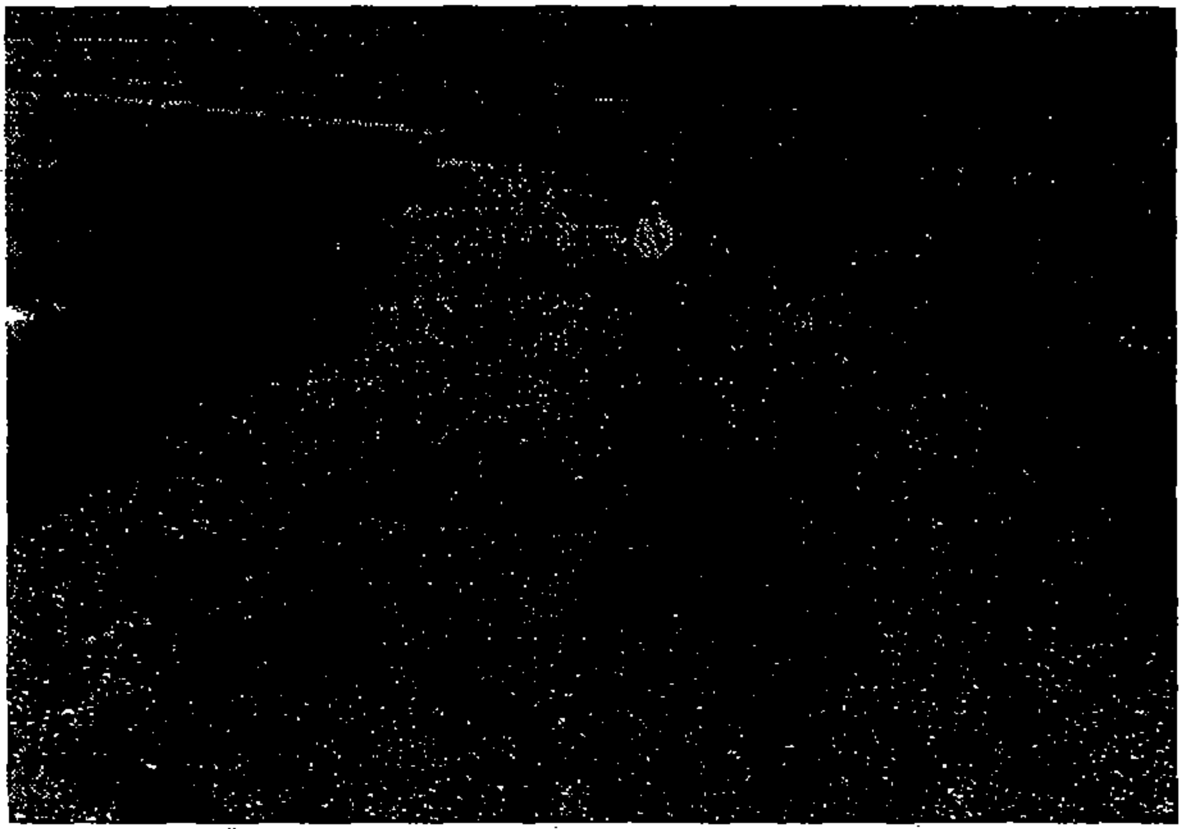


FIGURE 6-4. Roadway destroyed by thawing ice-wedges near Umiat. Gravel fill was not thick enough to replace insulating effect of the organic mat, which it destroyed. Photo taken by Gordon Greene.

buildings must be placed on the surface it is generally necessary to insulate and refrigerate their foundations; insulation alone only delays thawing. Although heated buildings generally are not built on grade, local warm surface patches from snow drifting against structures, or the above-freezing temperatures of well houses can be significant. If those disturbances are superimposed on others they must be considered in thermal design to avoid destructive thermokarst (see the section on "Well Pads" below).

Modified Lakes and Gravel Mines

Winters on the North Slope are cold enough to freeze lakes to a depth of about 1.8 m (6 ft). Most lakes and ponds on the North Slope are shallower than that, so they freeze solid to the bottom, and are part of the active layer. However, lakes that are deeper cross an environmental threshold—the bottom remains unfrozen, and a permanently thawed basin, or talik, grows downward into the permafrost under the lake bed. An inverted dimple of unfrozen ground grows upward from below the base of permafrost. If the lake area is large with respect to the natural depth of permafrost, and if the lake is old enough (thousands of years), the basin and dimple can join to form a thawed hourglass shape through the permafrost. Typically, the mean lake-bottom temperature is 1-2 °C (34-36 °F), or about 10 °C (18 °F) warmer than its surroundings (Brewer 1958b). In this sense deep lakes behave like heated buildings, and the same predictive theory for the thawed basin applies. When the lake is drained, refreezing of the sediments in the thawed basin beneath it often creates a pingo, a mound formed by ice expansion like the bump formed in the middle of an ice cube as it freezes.

If a shallow lake is deepened for a winter water supply, as is done occasionally, for example at Kuparuk, it will generally continue to deepen on its own from thaw settlement as its thawed basin grows. Once the lake no longer freezes to the bottom it works differently in the ecosystem. Gravel mines that become deep lakes behave similarly.

Gravel Roads

To prevent thermokarst, the gravel placed under roads must be thicker than its depth of summer thaw to ensure that the subgrade remains frozen as the road crosses a variety of thaw-unstable permafrost materials (Lachenbruch 1959). On the Arctic Coastal Plain this requires that roads be placed on gravel berms up to 2 m (6.5 ft) above the tundra surface. Like the elevated pipelines, this network of elevated roads has a conspicuous visual impact on the landscape. Additionally, the continuous berms intercept natural drainage, creating ponds that collect solar radiation, thicken the active layer, and initiate thermokarst (Walker 1996). Road dust also can perturb the thermal balance of the active layer and underlying permafrost. The effects of these processes on vegetation are described in Chapter 7.

Pipeline Burial

Permafrost poses severe obstacles to pipeline burial, the preferred mode of construction in nonpolar environments. The principal difficulty is that subsurface heat from the transmission of warm fluids thaws the surrounding permafrost, causing differential settlement, which strains the pipe. This consequence of permafrost leads to one of the most conspicuous impacts of oil and gas development on the North Slope—a network of elevated pipelines. They can impede free overland travel by subsistence hunters (newer ones are higher to permit passage) and they constitute an imposing visual alteration of the landscape (see Chapters 8 and 9).

The Northstar pipeline is buried in the seabed in a shallow trench that extends to an artificial island 10 km (6.2 mi) offshore. The pipeline has a planned operating temperature of 29 °C (85 °F); warm oil started to flow through it late in 2001. Special problems are posed by its burial in ice-bearing permafrost in the seabed within 3 km (1.9 mi) of shore (Intec Engineering 1998)—heat from the oil will eventually thaw the permafrost and strain the pipe. Although it has been carefully designed, such an offshore-buried pipeline is without precedent in the Alaskan Arctic; its performance will be instructive.

Well Pads and Annular Thawing

The layer of gravel used for roads is also generally adequate to protect large work pads from seasonal thaw settlement. However, different thermal designs may be necessary if there are additional sources of heat, such as the heated foundations of well houses, snow drifts that insulate pads from winter cold, or subsurface sources like heat in a "thawed chimney"—the annular region thawed through permafrost around a warm production well (see "Effects of Fluid Withdrawal").

The chimneys have become much more critical with the recent emphasis on decreasing the footprint using directional drilling from closely spaced wells on small well pads. In the process of drilling a well or extracting oil, natural gas, or formation waters, fluid circulating through a borehole transfers heat advectively from warm formations at depth to the colder ones near the surface. The drilling targets are generally at depths where the formation temperatures are 40-90 °C (104-194 °F). Heat from the warm fluid is conducted radially through the borehole wall (the well casing), quickly thawing annular zones, or chimneys in the surrounding permafrost (Lachenbruch et al. 1982a). The radius of the chimney is calculated by using properties of the permafrost and borehole specifications. For typical Prudhoe Bay production wells, Perkins and colleagues (1975) estimated a thawed chimney radius of about 2-6 m (6-20 ft) after a year or two and about 6-11 m (20-35 ft) after a decade of production. The smaller values apply near the surface where the permafrost is colder.

During the early Prudhoe Bay development, wells were drilled about 50 m (160 ft) apart (BP 1998a). Even after decades of production, thawed chimneys were relatively unconnected to one another, and most of the permafrost remained intact and able to resist damaging settlement (sometimes aided by insulating the well casings). In the current design, which is used for pads at the Alpine oil fields, wells at 43 °C (109 °F) are spaced only 3 m (10 ft) apart (Hazen 1999). Accommodating such a concentration of heat in permafrost requires sophisticated design with extensive refrigeration by passive heat pipes (or thermo-siphons) and insulation. Hazen (1999) calculated that, without refrigeration the thaw chimneys would coalesce at all depths, and all of the permafrost—about 300 m (1,000 ft) thick—under the row of wells would thaw. Then, the natural surface, gravel pad, and well houses would settle nonuniformly from 2 to 6 m (6.5-20 ft). With refrigeration to a depth of 15 m (50 ft) and insulated conductor pipe to 24 m (80 ft), Hazen (1999) estimated that all of the permafrost except for the top 12 m (40 ft) will thaw. That layer will remain intact to form a supporting arch that will deform slowly and smoothly, with only 30-60 cm (12-24 in.) of thaw settlement at the surface.

SUBSURFACE ENVIRONMENT: POSSIBLE EFFECTS OF THE WITHDRAWAL AND INJECTION OF FLUIDS AND OTHER MATERIALS

The subsurface physical environment in an oil field consists of the layers of sediment and rock and the fluids that naturally fill their fractures and pore space. Potential effects in this environment generally relate to its possible invasion by gas or oil along unintended flow paths through failed oil well casing and cement seals or through artificially fractured rock. Hydrocarbons—gas and oil—degrade two principle receptors: tundra surface habitats and subsurface water sources. On the North Slope oil fields the consequences are complicated considerably by the presence of permafrost and to some extent by waste-disposal practices. Problems related to the thawing of permafrost are mainly controlled by fluid withdrawal, the subject of the next section. However, in the North Slope oil fields fluids are injected into the wells in volumes comparable to those that are withdrawn; they too can have environmental consequences for the tundra surface and for subsurface water sources. Injection serves two purposes: It enhances production by restoring lost pressure in a waning reservoir, and it is used to dispose of drilling mud and other wastes by placing them in previously undisturbed porous rock strata. The first procedure has a long history of worldwide use; the second is relatively new and used most intensively on the North Slope. The first requires neither new flow paths nor injection pressures above natural ambient values—the second requires both. They are treated separately below.

Fluid Withdrawal and Its Effects

The fluids produced by a well are oil, gas, and formation water. In a typical reservoir, the shallowest portion can be filled with gas resting on oil that, in turn, rests on saline-to-brackish, rarely fresh, formation waters. As oil or gas is extracted, formation water moves up into the portion of the reservoir previously filled with oil and gas.

Those fluids are at temperatures and pressures that are largely controlled by the natural thermal gradient, the pressure gradient, and the depth of burial. The North Slope reservoirs are "normally pressured"; the rate of pressure increase and the pressure at any given depth are close to the hydrostatic gradient—0.427 kg/cm^2 per m (0.445 psi/ft). The initial reservoir pressure at Prudhoe Bay was 309 kg/cm^2 (4,390 psi) at 2,682 m (8,800 ft). In the shallower Kuparuk River field, the original reservoir pressure was 229 kg/cm^2 (3,250 psi) at 1,890 m (6,200 ft). The pressure gradients were 0.48 kg/cm^2/m (0.50 psi/ft) and 0.50 kg/cm^2/m (0.52 psi/ft), respectively, at Prudhoe and Kuparuk.

The thermal gradient determines the temperature of the fluids in the reservoir. It affects their viscosity, corrosiveness, and tendency to melt permafrost. The thermal gradient in the Prudhoe Bay Area is variable—its average is about 5.6 °C per 100 m (30.7 °F per 1,000 ft). The original temperature of the oil at the Prudhoe Bay Field was 97 °C (207 °F) at 2,682 m (8,800 ft); the temperature of the Kuparuk oil was 71 °C (160 °F) at 1,890 m (6,200 ft) (AOGCC 1998).

The withdrawal of subterranean fluids from oil fields in the Arctic causes thawing of the permafrost in the neighborhood of the wells. Ground that had been frozen solid loses its rigidity. This results in potential environmental and structural disruption.

Thawed chimneys create three potential problems that are specific to oil production in permafrost:

- *Annular path to the surface.* The thawed chimney is more permeable to infiltration by fluids than the same area is before disturbance. To the extent that permafrost might be expected to form a barrier to uncontrolled borehole fluids, the relatively permeable thawed chimney provides a possible path outside the casing for broaching to the tundra surface (ARCO/BP/Exxon 1997). Such a fluid path to the surface could affect natural plant communities, although no such effects have been observed.
- *Stress on the well casing.* The formation of the thawed chimney leads to two sources of stress on the well casing (Wooley & Associates 1996). The first is caused by thaw settlement when the annular region loses strength and settles against the casing adding axial (i.e., vertical) drag forces and radial pressures to the pipe. The second is caused by increased radial pressure as ice reforms during freezeback of the chimney after drilling or production ceases.

Alterations in casing design and cementing procedures seem to have solved problems of casing failure caused by external forces in the permafrost chimney (BP 2000, Perkins et al. 1975). A fluid with a freezing point below ambient temperature is commonly used inside the casing to prevent the internal forces caused by refreezing.

- *Surface subsidence.* When permafrost thaws, its volume decreases, leading to subsidence of the overlying ground and damage to structures on it. Producing oil wells on the North Slope thaw a chimney through the entire 300-600 m (1,000-2,000 ft) permafrost column beneath the pad that supports those structures. Understanding and controlling the surface effects are important. If the chimney were only a pinhole through permafrost, the surface material would not sink far into it before it would be supported by shearing stresses from the chimney walls. But if a chimney were wider than its height (thickness of permafrost) the walls could not support the slumping mass, and surface subsidence would be extreme.

In the older development areas where wells were drilled 36.5 m (120 ft) apart (BP 1998a), thawed chimneys did not coalesce and most of the permafrost remained intact and able to resist damaging settlement, especially if casings were insulated. However, wells are now being drilled so close together that, without additional mitigating measures, their thawed chimneys would coalesce to cause destructive differential settlement of the pads (see "Well Pads").

Injection for Enhanced Recovery

Fluids are injected into the subsurface for two purposes. The first is to increase the production of oil. The second is to facilitate more environmentally sound disposal of wastes produced during exploration and development. Several kinds of wells are used to inject fluids either for enhanced recovery or for disposal of wastes. Those wells must meet specific design requirements to isolate the injected fluids from the surface and to place them in specific horizons (Wondzell 2000).

The return of some produced fluids and the introduction of others to the producing formations is designed to improve the recovery of oil from the reservoir, either through maintaining pressure or through increasing the fluidity of the oil. To achieve this, produced fluids, such as formation water and gas, can be re-injected into the original oil-producing reservoirs. Other fluids, such as treated seawater and natural gas or CO_2 from other sources, also can be introduced to the reservoir.

Enhanced recovery requires that the fluid be beneficial for increasing the ultimate recovery of oil, that it be injected at pressures that will not propagate fractures through the confining zones that protect fresh waters, and that it be chemically compatible (for example, not to cause precipitation) with the formation water.

Formation water and treated seawater are used principally to maintain pressure. The water is placed in the reservoir by a series of injection wells to "push" the oil toward the producing wells. Natural gas and miscible injectants also are used to maintain pressure, but they have the added ability to increase the fluidity (decrease the viscosity) of the oil and strip it from sand grains (DOE 1999). The fluids generally are injected at depths below the oil-water contact surface to allow them to sweep through the entire oil column with maximum effect on any remaining mobile oil.

Potential environmental consequences would be the risk of escape of fluids to the surface either through fracturing of the overlying stratigraphic section (a highly improbable event) and the permafrost or around the casing through failure of the cement job or the casing itself. This could result in a spill on the tundra.

Injection for Waste Disposal

Environmentally sound disposal of oil-field wastes has long been a problem. A relatively recent innovation, the down-hole injection of fluid wastes and slurries, has been used for the disposal of large volumes of waste on the North Slope. These drilling by-products and other wastes are now injected into otherwise undisturbed, confined geological formations. Down-hole injection eliminated the use of reserve pits for surface storage of drilling waste (Gilders and Cronin 2000), and although it is superior in most respects to older methods, it is not without potential environmental effects.

Class I and II Wastes

Because of the presence of gas and oil, other volatile organic compounds, and metals, Class II (exempt) wastes present a considerably higher risk to the environment than do Class I (nonhazardous wastes), should there be a spill on the surface (API 1987, BP 1992). Such an event might result from a failure in the cement of the well, a pipe collapse, or through a nearby, poorly plugged or monitored, abandoned, or shut-in well. The actual down-hole effects of these fluids are unimportant if they are not injected into an underground source of drinking water (USDW).

Grind and Inject

The grind-and-inject process is used for Class II waste disposal of substances associated with reserve pits and drilling mud and cuttings from drilling wells. The process involves mining materials from the reserve pits, transporting them to a central grinding facility, grinding the solids finely enough to facilitate injection, and injecting them as a slurry into disposal zones (BP and ARCO 1993). The reserve pit solids contain a wide range of metals and some hydrocarbons, some of which present a potential hazard. (See Appendix D.)

Drilling mud and cuttings from active drilling wells also are ground and injected. More than 42 million barrels (bbl, 7 trillion L, 1.8 trillion gal) have been disposed of this way. This method of waste handling has greatly reduced the possibility of environmental damage caused by reserve pit materials. The hazards associated with subsurface injection of these materials are discussed below.

Annular Injection

Annular disposal is the process of pumping drilling mud and cuttings from drilling operations down the annulus formed when another casing is cemented inside the surface casing. Annular disposal requires porous intervals below the confining zone at the bottom of the surface casing and above the probable top-of-cement depth of the production casing. Only the drilling muds and cutting materials from the drilling operations compatible with disposal horizons can be injected. The ground and slurried materials are combined with water, if necessary, and pumped down the annulus and injected out of the bottom into the disposal formation. The result is a controlled fracturing of the disposal formation that creates more storage space and pushes the particulate material out into the porous formation. The water tends to separate from the cuttings and penetrates more deeply into the unit.

Alaska Oil and Gas Conservation Commission regulations limit the disposal volume to 35,000 bbl (5.7 million L, 1.5 million gal) per well to encourage the construction and use of disposal wells on drill pads and to reduce the possibility of the disposal stream eroding the production casing in the wellhead (Wondzell 2000). The amount is equivalent to the production of disposable materials from three wells.

At least 158 wells have been used for annular disposal of drilling muds and cuttings. A total of 3 million bbl (477 million L, 126 million gal) has been injected as depths of 820-1,340 m (2,690–4,400 ft). The potential hazards are discussed below.

Possible Effects of Injection for Waste Disposal

Pressure Fracturing and Broaches to the Surface

A potential concern is that the pressure required to inject wastes into a selected horizon might be enough to fracture the confining overburden stratum and allow waste to escape toward the surface. In the enhanced-recovery process this does not seem to be a serious problem because the injection augments the falling reservoir pressure and it takes place at pressures below the original ambient reservoir value. By contrast, waste injection is done in previously undisturbed subsurface environments and it requires pressures above ambient values. Where the waste includes ground rock cuttings, the target reservoir must be fractured to receive the slurry. This requires injection pressures that exceed the ambient by the fracture strength of reservoir rock, and poses a substantially greater potential for fracture of the confining overburden than is the case for enhanced recovery. Risk to confinement is much greater if the pressure fracture is vertical (not horizontal), an outcome predictable from a knowledge of the formation's stress state (Abou-Sayed et al. 1989).

Pressure profiles for several Prudhoe Bay wells confirm that the porous disposal formations now have pressures of 7-18 kg/cm^2 (100-250 psi) above the original hydrostatic

Ground Water Degradation by Waste Injection

In recent years, drilling wastes, which previously were stored in environmentally undesirable surface pits, have been injected into subsurface aquifers for permanent disposal. Although much of the water in aquifers below the impermeable permafrost is too saline to meet standards for a legally protected USDW, some is not. Because the sub-permafrost hydrologic system is poorly understood and incompletely sampled, the possibility of contaminating a potential water resource by waste injection should be considered.

The North Slope of Alaska is largely classified as wetlands underlain by permafrost, which separates the surface-water system—active layer, lakes, streams—from the relatively isolated and little understood groundwater system of sub-permafrost formations (Sloan 1987, Williams 1970). Although water appears plentiful on the surface, the North Slope has an arid climate, and if a significant supply of fresh water exists in deep aquifers it could be a valuable resource.

Extensive federal and state regulations are designed to identify potential USDWs and exclude them from waste-disposal programs. The federal Safe Drinking Water Act defines USDW as groundwater that contains less than 10,000 ppm (parts per million) total dissolved solids (TDS). Disposal in USDW is allowed only under special conditions (e.g., CFR144.3). The act essentially prohibits disposal in water with less than 3,000 ppm TDS (e.g., 40 CFR 146.4, 20 Aac 25.080(e)(1)). In aquifers where TDS exceeds 10,000 ppm there is no conflict regarding waste disposal. The TDS values needed to apply these regulations are generally inferred from well logs and are poorly known in detail. Relatively few direct chemical analyses are available from the North Slope.

Much but not all of the sub-permafrost groundwater in production areas is known to have salinities in excess of the 10,000 ppm limit. A map (Fink 1983) of West Sak Sandstone sub-permafrost water salinities shows that they range from > 50,000 ppm TDS in the northeast corner of the Prudhoe Bay unit to < 5,000 ppm TDS in the southwest corner of the Kuparuk River unit. Although those concentrations are generally based on estimates from down-hole resistivity logs, the low values in the Kuparuk River unit were confirmed by extensive chemical sampling showing TDS generally < 3,000 ppm (Fink 1983). Similar low values have been reported from widespread sub-permafrost chemical sampling elsewhere on the North Slope (Collet et al. 1988, Table II-9). Such results suggest that it might not be uncommon for sub-permafrost groundwater to meet the regulatory definition of USDW, but the extent is unknown and data on known occurrences have not been systematically compiled and published (see Chapter 10).

Findings

- Enhanced recovery procedures have not damaged the reservoir or other subsurface formations because of relatively low injection pressures and compatible chemistry.
- Production of fluids has not caused significant local or regional subsidence but the thermal effects of warm fluids promote thawing of the permafrost (creating thaw bulbs and chimneys) and could provide potential pathways for the escape of fluids to the surface around boreholes.
- There have been approximately 20 instances of broaching to the surface, primarily resulting from poor cement packages that cause leaks and from wellhead leaks. Engineering solutions have been effective to date.

- Groundwater resources—and the effects of waste injection on them—are inadequately examined and considered. Injection of drilling wastes into porous horizons has eliminated the problem of surface waste storage but has raised problems of possible groundwater contamination.

Recommendation

It should be confirmed that existing subsurface waste disposal practices are not depleting a groundwater resource intended for legal protection. Rigorously measured total dissolved solids profiles should be routinely acquired, compiled, and used to identify patterns of freshwater distribution as a tool for planning and for evaluation and conservation of the groundwater if appropriate.

ESCAPE OF INJECTED WASTE FLUIDS IN THE MARINE ENVIRONMENT

One concern regarding the effects of industrial activities on the marine environment is that injected waste fluids might travel laterally through a disposal zone to intersect the ocean floor. This is highly unlikely, however, because neither the producing reservoirs nor the disposal intervals intersect the ocean floor. Those units are buried hundreds to thousands of meters under younger rock and sediment. If such an occurrence were possible, one would expect numerous active large oil and gas seeps offshore from the major oil fields. They do not exist because the injection horizons are often as deeply buried as a number of the producing intervals, or as at Alpine, Kuparuk, and several of the satellite fields, the injection zones are deeper than production ones.

Surface Ballooning

Surface ballooning, or rebound, is a phenomenon that can be caused by injection of fluids. The possibility of this occurring on the North Slope has generated some concern. Surface rebound is known to have occurred in areas where a reservoir is relatively shallow compared with its lateral extent, there is a significant reduction in reservoir pressure, and the reservoir is relatively unconsolidated. Studies of the Cretaceous disposal intervals on the North Slope indicate that surface rebound is insignificant.

AIR QUALITY

Air quality on the North Slope has been affected by industrial activities there and elsewhere. The most important potential accumulation of effects is likely to be a reduction in visibility and an increase in direct human exposures to pollutants caused by synergistic interactions between locally generated and globally transported contaminants. Ecological degradation also could result from deposition of dust and pollutants on terrestrial and aquatic ecosystems.

Air quality on the North Slope meets state and national standards. Ambient concentrations of measured pollutants are often near detection limits at monitoring stations.

However, although local air quality does not appear to have been seriously degraded by emissions from oil and gas production facilities (AOGA 2001), emissions from local facilities result in observable haze, increased atmospheric turbidity, and decreased visibility (AOGA 2001).

The most conspicuous air quality problems on the North Slope are the widespread arctic haze, which occurs at higher elevations, and locally produced smog. Research confirms that arctic haze is a common phenomenon in polar climates and that it is the result of distant rather than local emissions. Fugitive emissions from industrialized areas in the temperate zone are transported long distances. There has been no research to determine how local and regional air masses and their contained contaminants interact. The lack of pre-development baseline data further hampers assessment of the effects of local or distant pollution on North Slope air quality.

If additional fields are developed, air emissions will increase. If more energy is required to maintain production in declining fields as waterflood or gas-lift injection are used to enhance oil recovery, air emissions could increase as well.

Findings

- The only areawide monitoring program on the North Slope has been for priority pollutants as defined by the Clean Water Act, from 1986 through 2002, at a limited number of sites. No large-scale, long-term monitoring system has been established to provide a quantitative baseline of spatial or temporal trends in air quality on the North Slope. The lack of adequate information limits the accuracy and precision of assessments of both past and future accumulation of effects.
- The quantity of air contaminants reaching the North Slope from distant sources is unknown.
- Little is known about the nature or extent of interactions between locally produced and globally transported air contaminants on the North Slope.

Recommendation

Research and monitoring should be implemented to distinguish between locally derived emissions and those that arrive by long-range transport, to determine how they interact, and to monitor potential human exposure to air contaminants.

FRESHWATER ENVIRONMENT

Industrial activities on the North Slope have to some degree affected the chemistry, flow patterns, and drainage patterns of the area's fresh waters. Effects could accumulate as a result of withdrawal or redistribution of water for construction of ice roads and pads, gravel mining in rivers, and blockage of drainage caused by gravel roads. Deposition of air contaminants also could alter water chemistry. Industrial activities to date have been concentrated in areas where lakes are common and there are abundant supplies of gravel. Those conditions do not characterize the foothills of the Brooks Range, many parts of the National Petroleum Reserve-

Alaska, or the Arctic National Wildlife Refuge. Therefore, the effects of future development on fresh waters in those regions could differ from those of the past.

Water Chemistry

During summer, inland lakes tend to have low concentrations of dissolved ions, but lakes near the coast that receive nearshore brackish waters have elevated concentrations of dissolved ions. As the ice grows in winter, electrolytes are excluded from the ice matrix and ion concentrations increase. By late winter or early spring, at maximum ice thickness, ion concentrations in unfrozen water can be more than four times greater than those observed during summer. Evidence suggests that no significant changes in seasonal patterns or concentrations of chemicals in lakes and streams have resulted from industrial activities on the North Slope.

Flow Patterns

Much of the gravel used for construction of roads and pads has been obtained from deposits within the floodplains of rivers. Concerns arising from this practice prompted the U.S. Fish and Wildlife Service to study the effects of floodplain gravel mining on physical and biological processes (Woodward-Clyde Consultants 1980). The study identified numerous examples of habitat modifications, including increased braiding and spreading of flows. The study also set forth guidelines on how to mine gravel to reduce floodplain effects (Joyce et al. 1980). As a result, gravel mining largely has been restricted to deep mining in upland pits, some of which are flooded on abandonment to create aquatic habitat.

Drainage Patterns

Much of the gravel used for roads and pads has been deposited in wetlands. During spring break-up there are substantial sheet-flows across the wetlands of the Arctic Coastal Plain into lakes and streams. When long stretches of gravel road interrupt flows, the difference in water surface elevation from one side of the road to the other can produce high flow rates in the cross-road drainage structures. An opposite effect can occur in mid-to late summer when stream flow is low.

Findings

- Gravel mining in rivers during the early years of development substantially altered flow patterns and distribution of unfrozen water in winter, but recent restriction of gravel mining to upland pits has reduced those effects.
- Gravel roads and pads have often interrupted both sheet flow and stream flows. Proper construction and placement of culverts can greatly reduce but not eliminate those effects.
- Development in areas where surface water is less abundant could result in effects on fresh water that differ from those in the freshwater-rich Prudhoe Bay region.

MARINE ENVIRONMENT

Offshore activity in the Beaufort Sea has been limited. Activities that affect the quality of marine waters and flow patterns have included construction of gravel islands and causeways and discharges of materials. Only a few small spills have occurred in marine waters to date, but mechanical recovery—the method allowed by current regulations—is not efficient and only removes a small fraction of the spilled oil, especially in broken ice. Concerns about contamination of marine waters center primarily on the potential effects on marine organisms. Those effects are discussed in Chapter 8.

There have been three permitted types of discharges to the Beaufort Sea over the life of the oil fields. First, individual facilities have discharges permitted under U.S. Environmental Protection Agency (EPA) NPDES (National Pollution Discharge Elimination System) program. Second, small or localized discharges have been permitted under the North Slope General NPDES Permit (under EPA). Third, exploratory drilling discharges were permitted under the Arctic General (or Beaufort General) NPDES Permit under either coastal effluent guidelines or offshore effluent guidelines (Wilson 2001b).

Permitted NPDES discharges include effluents from seawater-treatment plants, desalination plants, sanitary-waste-processing units, deck drainage sumps (from offshore production facilities, such as Northstar), temporary construction dewatering, and occasional tests of fire suppression with water. These discharges are permitted for a specific facility, and there are monitoring and reporting requirements. Four facilities currently have NPDES permits: Northstar, the Prudhoe Bay seawater treatment plant (STP), Kuparuk STP, and Endicott. The largest discharges under this program are ocean water and peat detritus from the two STP operations (Wilson 2001b).

A North Slope General Permit was issued by EPA for small operations other than those covered under individual NPDES permits. Permitted discharges include small volumes of water pumped from gravel mine sites and wastes from temporary camps. Industry must apply to EPA for coverage under the general permit. Discharges are small, localized, and infrequent.

Exploratory drilling discharges are covered under the EPA Beaufort Sea General Permit and include disposal of drill cuttings and fluids from well-drilling operations. Which effluent guidelines are in effect depends on whether the well is drilled near to the shore or off shore. The coastal effluent guidelines in effect since the mid-1990s prohibit discharge of muds and cuttings. Offshore guidelines still allow discharges of muds and cuttings.

Monitoring is frequently required as a condition of discharge permits to ensure that discharges do not exceed water quality standards, are not toxic to marine organisms, do not degrade water quality, and do not pose a threat to human health. Most of the records of the monitoring programs are retained by EPA, the principal permitting agency, and are not readily available. Records also are kept by individual operators, but those records are not summarized, and few annual reports have been produced.

NPDES Monitoring

Until recently, NPDES stipulations have called for environmental monitoring for all operations covered by the permits. The studies have included monitoring the waste stream as well as the receiving water. Topics include effluent mixing and dispersion, and the effects of effluents on fish, benthic organisms, sediments, and water quality. Permits generally required that water, sediment, or biological samples be obtained seasonally from within and outside of the outfall mixing zone. Required monitoring of fish and benthic communities has been discontinued in recent years because effects were found to be minor or not measurable (Wilson 2001a).

Water-quality monitoring has included measurement of several variables in the receiving water, including currents, salinity, temperature, pH, dissolved oxygen, total suspended solids, total residual chlorine, and chlorine reaction products. Sediment studies have measured grain size distribution, total volatile solids, and concentrations of organohalide compounds. Biological monitoring has included collection of fish and benthic organisms and toxicity studies that use commercially available test organisms (Robilliard et al. 1988, Wilson 2001b).

Results of monitoring water quality, sediments, and species for the Kuparuk STP outfall were summarized by Montgomery Watson (1994). The results of winter and summer measurements of temperature, salinity, dissolved oxygen, pH, total suspended solids, and total residual chlorine showed values that were within permitted ranges both within and outside of the mixing zone. Sediment monitoring at the Kuparuk STP outfall revealed no adverse effects of the discharge on sediment grain size. Some variability was noted in silt, clay, and other grain sizes at some sampling stations. Total volatile solids showed a pattern of increasing concentrations from west to east across the study area. This was attributed to variations in natural peat detritus across the sampling-station array.

Finding

Physical effects of discharges and spills have been small and infrequent and have not accumulated. The effects of causeways are discussed in Chapter 8.

7

Effects on Vegetation

As a result of oil and gas exploration and development, vegetation on Alaska's North Slope has been affected by diesel fuel, oil, and saltwater spills; by disturbances related to roads and gravel pads; and by damage attributable to seismic exploration (Forbes et al. 2001, Jorgenson and Joyce 1994, McKendrick 2000b, Walker 1996). These direct physical effects can reduce the insulating quality of the vegetation and cause additional disruption of the surface ("thermokarst") by thawing the underlying ice-rich permafrost (Chapter 6). Because most industrial activity has been concentrated on the Arctic Coastal Plain, data about the accumulation of effects on vegetation come primarily from that region. However, as industrial activity spreads south into the foothills of the Brooks Range, it will affect vegetation types not previously influenced. In addition to summarizing those specific classes of effects this chapter examines areas of special biotic importance and the challenges that attend removal of facilities and rehabilitation of gravel areas, including regulatory issues.

SPILLS AND CONTAMINANTS

Oil spills on the North Slope have been smaller than have been spills in other oil producing regions of the world. The largest spill in the North Slope oil fields covered 1,700 m^2 (18,300 ft^2) of tundra, and no other spill has exceeded 500 m^2 (5,400 ft^2) (McKendrick 2000b, Appendix F). For comparison, the 1994 Usinsk oil spill in Russia covered about 70 km^2 (27 mi^2) of terrain and released some amount between 93-114,000 metric tons (102-126,000 tons) of oil, causing an estimated $15.5 million in damage to aquatic resources in three large rivers, destroying 200,000 m^3 (262,000 yd^3) of forest, and sparking large polluting fires (Vilchek and Tishkov 1997). Spills of that magnitude have been avoided in Alaska because of the system of monitoring and check valves in all pipelines. To date, most North Slope contaminant spills have occurred on gravel pads, which have minimized the extent of the effects. Contaminant spills on tundra, however, can cause significant damage to vegetation. The effects of spills vary by the season, the vegetation, and the substance spilled. A winter spill on frozen tundra is easier to clean up than is a spill in warmer periods because the contaminants can be removed as frozen material from the surface (McKendrick 2000b). As would be expected, some plants are more sensitive than others: The most sensitive vegetation is found in dry areas, and some plants, such as *Dryas* and *Sphagnum*, are particularly sensitive.

Generally one of three substances would be spilled: oil as it is drilled or transported for processing, diesel fuel stored for or in use by oil and gas exploration and development equipment, and saline water (seawater used in oil recovery operations or for testing pipelines or saltwater produced as a by-product of oil extraction). The damage can persist: Diesel fuel can remain in tundra soils for more than 20 years with little recovery of plants in affected areas (Walker et al. 1978).

Saltwater spills, although uncommon, are especially problematic. Salts are not biodegradable and they are toxic to many plant species (Simmons et al. 1983): *Dryas* and deciduous shrubs that grow in wet ground, including dwarf willows (*Salix* spp.), are the most sensitive, and sedges that grow in wet places (*Eriophorum* and *Carex*) are the most resilient to saltwater. The standard response to saline water spills is to flush the spill site with fresh water, which reduces effects and promotes more rapid recovery. Colonization by salt-tolerant species, such as *Dupontia* grass, eventually occurs (Jorgenson and Joyce 1994), but recovery of the most sensitive plants can take several years. The extent of a seawater spill is difficult to detect at the time of the spill without chemical testing of the soils.

Old reserve-pit fluids also contain salts (French 1985). The toxicity of the fluid varies seasonally and from one pit to another (Myers and Barker 1984), but it tends to decrease as pits age because of dilution by snowmelt waters. The plant species most affected by reserve-pit fluids are the same as those affected by saltwater spills (Myers and Barker 1984, Simmons et al. 1983). Recent grind-and-inject techniques have largely eliminated new contamination by reserve-pit fluids. Soil salinity also contributes to the difficulty of rehabilitating disturbed sites in some areas at Prudhoe Bay, where calcium carbonate concentrations are naturally high and summer precipitation is low (Jorgenson and Joyce 1994).

Studies of the effects of oil contamination of vegetation in the Prudhoe Bay region indicate that moderate concentrations—about 12 l/m^2—can result in the death of most plant species (Walker et al. 1978). Several common species of deciduous shrubs (*Salix* spp.) and sedges (*Carex* spp. and *Eriophorum* spp.) and a few aquatic mosses (e.g., *Scorpidium scorpioides*) are more resistant. Recovery in areas where the soils are saturated with oil to a depth of more than 10 cm (4 in.) is very poor after 12 years (Walker et al. 1978). Long-term recovery from light to moderate oil spills is usually better because the toxic components break down over time.

Oil spilled on wet tundra kills the moss layers and aboveground parts of vascular plants, and sometimes kills all macroflora in the affected area (McKendrick and Mitchell 1978). Because tundra acts like a sponge, spreading is limited and generally only small areas are affected (BLM 1998). But those effects can be severe, and recovery from tundra spills can take 10 years or more (McKendrick 1987). In general, spills that saturate the tundra produce severe, long-lasting effects and recovery is slow. Walker (1996) reported that recovery from diesel fuel spills also proceeds slowly. Twenty-eight years after a spill at Fish Creek, little vegetation recovery was evident and the fuel was still present in the soil. Places where crude oil and crankcase oil had spilled showed better results after 28 years, except in the areas of heaviest effect. In experimental spills (Walker et al. 1978) of crude oil and diesel fuel, tundra plant communities on diesel fuel plots showed no recovery after 1 year. There was some recovery of sedges and willows after 1 year on the crude oil plots. However, mosses, lichens, and most dicots showed almost no recovery. Walker and colleagues (1978) suggested that vegetation spill-sensitivity maps can be developed. Natural seeps also can affect vegetation; sedges seem to be among the most tolerant plants (McCown et al. 1973).

Many bioremediation techniques have been used within the oil fields (Jorgenson and Joyce 1994): Microbial degradation has been enhanced by fertilizer treatment, aeration, and hydrologic manipulation (Jorgenson et al. 1991). Burning of spilled oil and thermal remediation also are used (Jorgenson and Joyce 1994). The oil industry has developed technology to prevent, clean up, and rehabilitate most terrestrial contaminant spills, but techniques for optimizing the microbial degradation of hydrocarbons in tundra soils still needs development. Although the effects of contaminant spills could accumulate if the size and frequency of spills were to increase, their effects have not accumulated to date on North Slope vegetation. Oil and saltwater spills are described in detail in appendixes F and G.

Most of the literature on the response of tundra vegetation to contaminant spills has been from short-term observations, 1-3 years. Longer term studies are needed to determine the recovery potential of various plant communities and for use in developing maps that will show areas of sensitivity to spills and those in which there would be a good possibility of recovery from a spill.

ROADS AND GRAVEL PADS

There is an extensive, increasing network of roads and gravel pads on the North Slope (Figures 4-3–4-6). The effects of gravel pads on vegetation are usually localized, but roads (especially old roads and those more heavily traveled) have a variety of sometimes far-reaching effects on plants and animals and can cause broad changes to ecosystem structure and functioning. Roads directly cover and kill tundra vegetation, but their effects extend beyond their footprints. Roads can displace wildlife, impede wildlife movement, and increase human access to an area. They are visually conspicuous, change hydrological patterns, and assist in the dispersal of nonnative plants (Ercelawn 1999). Road-related changes that are unique to cold regions include alterations of snow distribution patterns and creation of thermokarst (irregular depressions caused by melting and heaving of frozen ground) (Walker et al. 1987a).

The Prudhoe Bay region has a variety of road types. Roads to remote drill sites are rarely traveled; roads that link oilfield structures are heavily used. As would be expected, wide, more heavily traveled roads cause more severe indirect effects: heavy road dust, hydrology changes and flooding, altered snow distribution, thermokarst, increased accessibility to associated off-road-vehicle trails, and greater opportunity for invasion by nonnative plant species. Hunters, tourists, and other users cause additional effects in a broad area along the Dalton Highway corridor. The effects of dense networks of roads and gravel pads are complex—several roads can influence the same piece of ground. Roadside structures, such as pipelines, power lines, power plants, and industrial centers, can make large areas of land unavailable or undesirable to wildlife, subsistence hunters and wilderness travelers.

Old Roads, Exploration Trails, and Drill Sites

When exploration of the North Slope began, knowledge about of the effects of exploration and construction techniques on permafrost was limited. From early exploration through the 1950s, trails often were cut directly into frozen ground. Large tractors and tracked vehicles traveled over thawed ground in the summer, often leaving deep ruts, and sometimes road builders removed the vegetation mat completely, causing deep thermokarst (Bliss and Wein 1972, Chapin and Chapin 1980, Hernandez 1973). Trails commonly became wetter than the natural habitat and were colonized by species more adapted to wet sites. Higher biomass and changes in nutrient concentrations occurred in the trails (Chapin and Shaver 1981). At times, subsidence and erosion created trails as deep as 5 m (16 ft) (Lawson et al. 1978). Some old trails and seismic surveys made by government contractors in the 1940s are still clearly visible because they are deeply rutted, often flooded, and filled with vegetation that is quite different from the surrounding tundra (Hok 1969, 1971; Lawson et al. 1978).

In the 1960s, peat roads were built by scooping the active layer from two sides of an area and piling it in the center to form an elevated surface. This method also resulted in severe thermokarst. By the 1970s, gravel had replaced peat in road construction. Now in many cases, ice is used.

There has been a parallel evolution in the techniques used to build drill sites. Many of the early exploration wells were drilled without gravel pads. In some cases the drilling wastes were deposited directly on the tundra. As environmental awareness increased, drilling wastes were contained in reserve pits, which often leaked. The consequences for those old reserve pits on the arctic vegetation pose special challenges for rehabilitation.

Modern Roads and Gravel Pads

The currently preferred method for road and site development is to build a thick gravel pad, often more than 2 m (6.5 ft) thick, to insulate the underlying permafrost. Sometimes polyethylene insulation is placed below the pads to reduce the amount of gravel needed. If a pad is temporary, a thinner layer of gravel or sand is used. Thick gravel pads that protect the permafrost cause other environmental effects: They create dry elevated areas that are difficult to rehabilitate after a pad is abandoned, they require gravel mines whose sites also must be rehabilitated, they block natural drainage channels, and they alter snow-drift patterns. The direct and indirect effects of the Dalton Highway, the Prudhoe Bay roads, and the Trans-Alaska Pipeline Corridor have been studied extensively (Auerbach et al. 1997, Brown and Berg 1980, Klinger et al. 1983b, McKendrick 2002, Pamplin 1979, Walker 1996, Walker et al. 1987a).

Road Dust

Dust is an inevitable by-product of the use of gravel roads on the North Slope (Figure 7-1). Dust loads are highest along the Spine Road and, until 2002, when it was chip-sealed, the Dalton Highway, where traffic is heavier and faster than on other area roads. One study showed that as much as 25 cm (10 in.) of dust had been deposited in some areas along the Spine Road (McKendrick 2000b). Earlier studies reported that all vegetation was eliminated within 5 m (16 ft) of the most heavily traveled roads at Prudhoe Bay. Mosses were eliminated to about 20 m (66 ft) (Auerbach et al. 1997, Everett 1980, Walker and Everett 1987). Dustfall 1,000 m (3,280 ft) from the road was several times higher along the Spine Road than at the other sites because of the heavier traffic (Everett 1980). In acidic tundra regions, the normally high buffering capacity of the tundra was neutralized by the heavy dustfall. At an acidic tundra area in the foothills, the pH in roadside areas has shifted from acidic to alkaline (pH 4.0 to pH 7.3) (Auerbach et al. 1997).

Several road-related phenomena interact to increase the depth of the tundra's active layer. The elimination of the moss carpet reduces insulation, and deep snow drifts accumulate near the

(a)

(b)

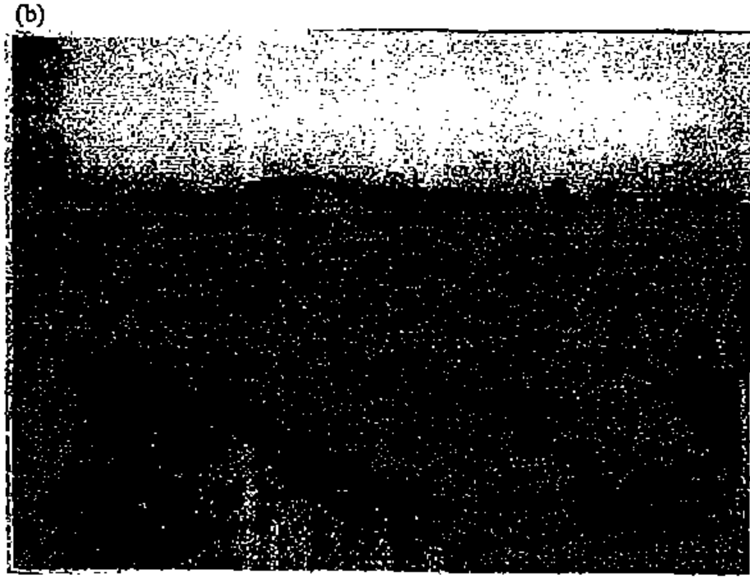


FIGURE 7-1. (a) Trucks raising dust plumes along the Dalton Highway. Truck speeds often exceed 60 mph, and winds can distribute the dust to distances of more than 1 km from the road (Everett 1980). Chip sealing, which is now being done, reduces dust along the Dalton Highway. (b) Environment along the Prudhoe Bay Spine Road. Barren areas are caused by thick dust, and ponded areas are caused by thermokarst. This was formerly an area of low-centered polygons that was converted to high-centered polygons by erosion of the polygon troughs. Source: Walker 1996. Reprinted with permission, copyright 1996, Springer-Verlag.

roads, increasing the wintertime soil surface temperature. Despite the deeper snow associated with elevated roads, the snow melts earlier because the darker, dust-covered snow surfaces absorb more heat. Ponds near roads also absorb more heat. All of these factors combine to warm the soil, deepen the thaw, and produce thermokarst adjacent to roads. The earlier snowmelt near roads also can open these areas to wildlife several days or weeks before adjacent snow-covered tundra areas become accessible (Walker and Everett 1987). Tracts of dust-killed vegetation have expanded from those observed in 1980s, and thermokarst, which was spreading rapidly during the 1980s (Walker et al. 1986b, 1987b), continues to spread along ice-wedge polygon troughs. Changes along the roads have not been documented consistently, and detailed long-term studies are needed. Paved roads produce far less dust, and chip-seal treatments (an application of asphalt followed with an aggregate rock cover) have reduced dust along the Dalton Highway and some other roads.

Roadside Flooding

Flooding, another major effect, is generally confined to wet and aquatic tundra vegetation. Most road-related flooding occurs where roads cross low-lying, drained thaw-lake basins. Drainage patterns on the flat tundra are complex, and there are many unconnected drainage systems. In areas where there is an intersecting web of roads, such as around the Prudhoe Bay development, flooded areas are more common and often difficult to drain (Figure 7-2). The road to West Dock, constructed in 1980-1981, is 7 km (4 mi) long, crosses four drained lake basins, and caused flooding to about 131 ha (324 acres) of tundra (Klinger et al. 1983a). It is difficult to position culverts along such roads because the routes of melt water drainage often are not detectable at the time of road construction. Even if culverts are located appropriately, they generally are frozen at the time of the spring melt. In deeply flooded basins, elevated microsites, which are important nesting areas for some bird species, are submerged and thus unavailable during the nesting season (Walker 1997).

Invasion of Nonnative and Native Species

Nonnative species have sometimes been introduced in seed mixtures and mulches during rehabilitation efforts (Johnson 1981, Kubanis 1980). Surveys along the Dalton Highway during the late 1970s showed that 13 plant species had been introduced, and 9 of them were reproducing (Kubanis 1980). However, none of those species has been documented as successfully invading native-plant communities. Climate change could cause more species to invade the North Slope. Current rehabilitation research focuses on natural revegetation with minimal application of nonnative seed mixes (Jorgenson et al. 1997a). Vegetation patterns also can be altered when native species that grow naturally in other areas move into disturbed sites (e.g., dusted areas, seismic trails, snow pads) (Emers et al. 1995, Johnson 1981, McKendrick 2000b). The grass *Arctagrostis latifolia* often invades those areas, but others species do as well depending on the severity of the disturbance. Coastal and dune plant species can colonize severely dusted areas well inland (McKendrick 2000b). Overall, invasion by nonnative species has not been an important problem.

FIGURE 7-2. One of the four lake basins along the Waterflood road at Prudhoe Bay. The photo was taken in early summer before ice in the culverts thawed. By late summer the large oval impoundment drained, but the vegetation changed over a period of 3 years. Notice the lack of elevated microsites for bird nests in the flooded areas compared with the other side of the road. Also note the other impoundment along the road (arrow), which does not drain all summer. Source: Walker 1996. Reprinted with permission, copyright 1996, Springer-Verlag.

Estimates of Indirect Effects

Few detailed analyses of the growth of the oil-field infrastructure assess indirect effects such as dust, flooding, and thermokarst. Nor do they address the various types of habitat lost to direct and indirect effects. Such analyses require a time-sequence of detailed photo-interpreted maps that show the ecological communities of a region before development and maps of the direct and indirect effects for several years during development. One such an analysis was performed for three heavily disturbed portions of the Prudhoe Bay oilfield. Figure 7-3 illustrates one section (Walker et al. 1987b).

Although there are no data to delineate the extent of the indirect physical effects of the North Slope's road network, historical mapping studies from the 1980s showed that wide margins on both sides of roads were affected by dust, thermokarst, intermittent flooding, gravel spray, vehicle trails, and trash (Walker et al. 1987b). The width of the margins varied according to the amount of traffic and the terrain type. Very flat portions of the oil field with many drained thaw lake basins and many roads had extensive areas of roadside flooding that greatly exceeds the gravel-covered areas of the roads and pads (Figure 7-3).

Effects of ground excavations were most widespread in the floodplains, whereas effects of dust and thermokarst were most extensive on the upland areas. In a very wet area of a heavily affected portion of the oil field, the ratio of indirect effects (roadside flooding, dust, debris, thermokarst) to the area of the gravel road was 8.6:1. In dry areas of the same heavily developed portion of the field, the ratio was 2.4:1, and the mean for all mapped areas (mostly in heavily developed portions of the field) was 6:1 (data derived from Walker et al. 1986b).

Walker and colleagues (1987b) focused on some of the most severely affected areas of the oil field—areas that were developed first but that no longer represent development practices (Robertson 1989). Their study is, however, an important reference for changes within the oldest, main part of the oil field. Their methods could be used again to examine more recent changes and used elsewhere to assess effects in areas where newer technology has been used.

SEISMIC EXPLORATION

Some seismic trails from the 1940s are still visible on the North Slope. There are no maps that show all of the early trails, so an estimate of their total length cannot be calculated. Many studies of the effects of off-road vehicles have noted critical factors that determine the amount of damage to the tundra (Abele et al. 1978, 1984; Radforth 1972, Walker et al. 1977):

- ground pressure
- total weight of each vehicle
- number of passes by the vehicles
- terrain
- type of vegetation

The development of new methods for seismic exploration might reduce damage by reducing the weight, tracks, or the number of vehicles used.

Nearly all of our knowledge about long-term recovery from seismic exploration comes from a single U.S. Fish and Wildlife Service (FWS) study of a 2-D (two-dimensional) seismic survey in the Arctic National Wildlife Refuge in 1984-1985 (Emers and Jorgenson 1997).

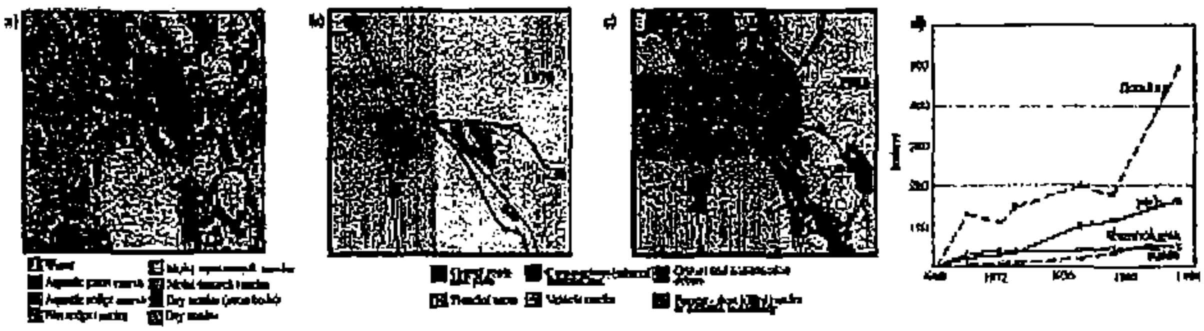


FIGURE 7-3. Geobotanical and historical disturbance mapping. The area shown is among the most heavily developed portions of the oil field. (a) Vegetation map shows the terrain as of 1949, before development. Soils and landforms also were mapped. (b) Infrastructure as of 1970, with a few roads and drill sites. Some flooding (violet) and roadside disturbances (red) are evident. (c) Infrastructure as of 1983. Source: Walker 1996. Adapted from Walker et al. 1987b. Numerous large pads include the processing facility at GC-1 (center) BP base operations camp (lower right), a construction camp (northwest of GC-1), and several production pads. The roads and pads inhibit drainage, and there is extensive flooding in the drained thaw effects in lake basins. (d) Progression of direct (solid lines) and two indirect effects (dashed lines). The area of indirect effects in this portion of the oil field was nearly triple the area of the direct effects. Source: Alaska Geobotany Center, adapted from Walker et al. 1987b.

Although technology changes since then limit the applicability of its results, the study does provide valuable information on different types of effects and on the recovery rates of tundra.

According to Emers and Jorgenson (1997), the 1984-1985 seismic exploration consisted of more than 2,000 km (1,200 mi) of seismic lines, arranged in 5 x 20 km (3 x 12 mi) line spacings. Another 2,000 km of trails was associated with moving the support camps. Most seismic lines consisted of a multitude of trails caused by multiple passes by a variety of vehicles (Figure 7-4). Camp-move trails caused more damage than the seismic lines did, however, particularly when the snow cover was insufficient to protect the ground and the tractors scraped the tundra as their treads sliced through the vegetative mat.

Effects were estimated from an aerial photo survey that examined a random sample of 20% of the trails a year after disturbance. About 14% of the trails showed no detectable disturbance; 57% had low disturbance; 27% had moderate disturbance; and 2% had high disturbance (Raynolds and Felix 1989). Eight years after the exploration, only about 3% of the seismic and receiver line trails were still disturbed, but camp-move trails showed more disturbance—about 10% were disturbed, including 4% that showed medium disturbance and 1% that showed high disturbance (Emers et al. 1995).

Figure 7-5 shows examples of damage caused by seismic-exploration vehicles. Effects are rated on a 4-point scale with 0 indicating no damage and 3 indicating extensive disturbance of vegetation.

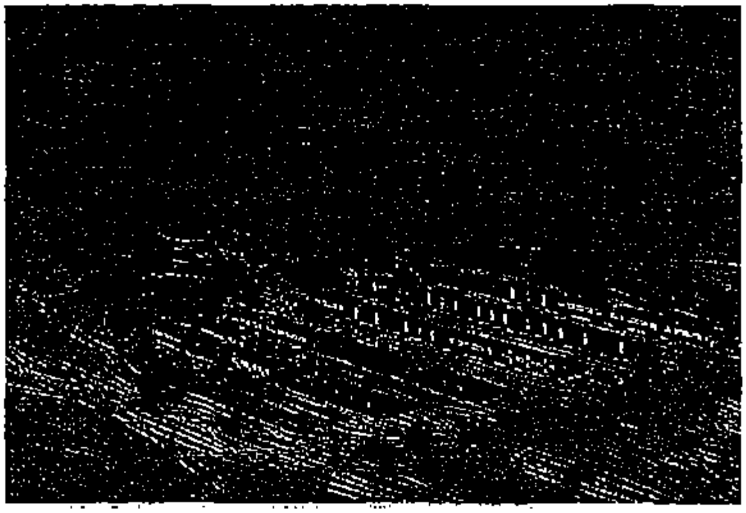
Although the typical effects of individual seismic trails in the Arctic National Wildlife Refuge generally were minor, they were extensive and varied greatly with vegetation type, terrain, vehicle type, operator vigilance, and amount of snow cover. Minor effects and rapid recovery occurred in flat areas of wet tundra, which are common on the Arctic Coastal Plain. Damage was greater in areas with more microrelief and in areas with taller shrubs that were not covered by snow, which is more common in hilly portions of the North Slope. Tussock tundra and frost-boil tundra were particularly susceptible because of higher microrelief.

The greatest damage occurred where the vegetative mat was destroyed and the underlying soil was exposed. This was infrequent and usually result from tracked vehicles or sleds on skids cutting into hummocks or other raised areas or from Caterpillars operators making a tight turn or dropping a blade too deeply into the snow. High disturbance also occurred where vehicles became mired in deep snow and their operators tried to extricate the equipment instead of being pulled out (Shultz 2001). The most common sites of high disturbance were in areas with low snow cover and where vegetation is easily disturbed—river terrace plant communities or plant communities on stabilized sand dunes.

The plant species that are most sensitive to disturbance and that have poor potential for recovery are among the most common. Cottongrass tussocks (*Eriophorum vaginatum*) are susceptible and often are crushed or cut open by the grouser bars on tracked vehicles, as are evergreen shrubs (*Rhododendron decumbens, Vaccinium vitis-idaea, Dryas integrifolia*), some deciduous shrubs (*Betula nana, Arctostaphylos rubra, Salix phlebophylla, S. reticulata*), some mosses (particularly *Sphagnum* and *Tomentypnum nitens*), and all lichens (Felix et al. 1992). Some affected species, such as Labrador tea (*Rhododendron decumbens*) and low-bush cranberry (*Viburnum edule*), are used extensively by the Inupiat, who have concerns about the effects of seismic trails on their subsistence harvests. The physiological reasons for the sensitivity of certain species are not known.

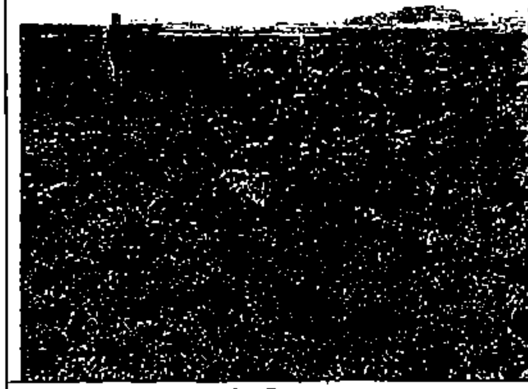
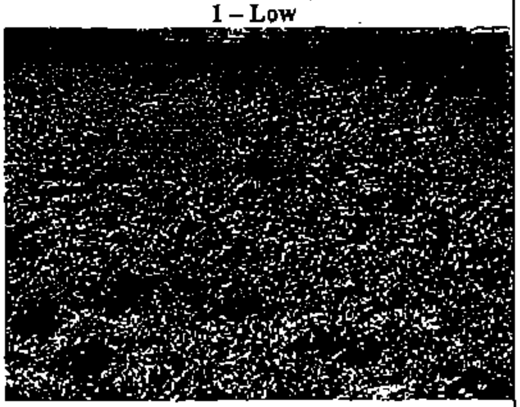
In 1998, 14 years after the original survey, 7% of the plots assessed on the ground were still disturbed, and 15% showed disturbance that was visible from the air (J. Jorgenson, FWS,

(a)



(b)

FIGURE 7-4. (a) Trailers on skids make up Camp 794 on the tundra of the National Petroleum Reserve-Alaska. Photo courtesy of the *Anchorage Daily News*. (b) Tractors towing camp trailers during a camp move. Source: U.S. Fish and Wildlife Service.

0 – None 	No effect of slight scuffing of higher microsites. *Trail goes through photo from foreground to background, passing between the two wooden stakes in the distance. Note slight color difference in tussocks on trail (light brown color rather than gray), due to scuffing of tops of tussocks.*
1 – Low 	Less than 25% decrease in vegetation or shrub cover; less than 5% soil exposed. Comparison of standing litter and slight scuffing in wet graminoid and moist sedge-shrub tundra. Tussocks or hummocks scuffed. Trail evident only with tracks on Dryas terrace sites. *All of the foreground and much of the background of this photo show tussocks disturbed by dispersed vehicle traffic. Note the flattened, brown-topped tussocks, compared to the tussocks with level 0 disturbance pictured above.*

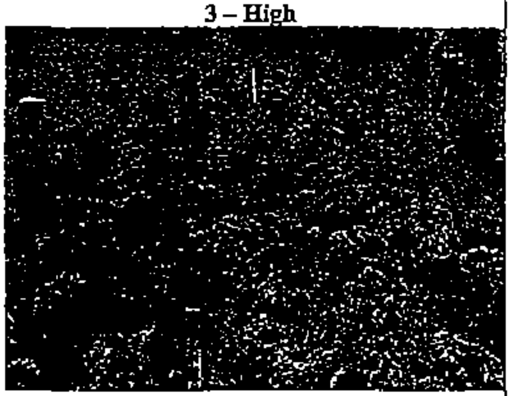
2 – Moderate 	Vegetation or shrub cover decrease 25-50%, exposed soil 5-15%. Compression of mosses and standing litter in wet graminoid and moist sedge-shrub tundra; may have increase in aquatic sedges. Tussocks or hummocks crushed but show regrowth. Portions of trail may appear wetter than surrounding area. Some disruption of vegetative mat within tracks of riparian shrublands and Dryas terrace. May be some change in vegetative composition. *Note the two vehicle tracks going from foreground to background. Tussocks in the tracks are crushed.*
3 – High 	Over 50% decrease in vegetation cover or shrub cover; over 15% soil exposed. Obvious track depression in wet graminoid and moist-shrub tundra; standing water is apparent on trail that is not present in adjacent areas in wet years; moist sedge-shrub tundra changing to wet graminoid. Crushed tussock or hummocks nearly continuous; general depression of the trail is evident; change in vegetation composition. In riparian shrub and Dryas terrace vegetative mat and ground cover substantially disrupted. *Note the exposed soil and crushed tussocks on the trail.*

FIGURE 7-5. Examples of seismic-exploration disturbance on tussock tundra vegetation.
Source: U.S. Fish and Wildlife Service.

personal communication, 2001). The active layer was deeper on about 50% of the disturbed plots than it was in adjacent control areas after 10 years (1984-1994). By 1998, differences in thaw were still noticeable on many of the trails. Based on the current recovery rates, the long-term trends each disturbance category can be illustrated (Figure 7-6). Overall, the vegetation recovery reaches a plateau after about 8 years. Some trails are likely to be visible from the air for decades after that (Jorgenson, unpublished, 2001) (Figure 7-7).

Few studies have examined the effects of current three-dimensional (3-D) seismic methods. One study of the Colville River delta detected the trails left from repeated 2-D exploration in 1992, 1993, and 1995 and from 3-D work in 1996, but it reported generally minor disturbance (Jorgenson and Roth 2001). High disturbance occurred on only 1% of the sites surveyed, mostly dry dune areas. Maps of those survey lines show the much higher density of trails associated with the 3-D operations, which can be spaced as close as 200 m (660 ft), or rarely even closer. It was difficult to quantify the numerous random stray trails that were not part of the seismic lines or camp-move trails (for example, see Figure 7-7a). Some areas were surveyed several times by different companies, resulting in a maze of seismic trails, camp trails, and ice roads, which are difficult to separate or identify by type and year of origin. Some repetition is caused by the need for new or better seismic information, but it also occurs because the data are proprietary and companies will not share information that might help competitors, thus setting the stage for each to gather data and conduct analyses independently.

The Importance of Snow Cover

The Alaska Department of Natural Resources (DNR) issues tundra travel permits for seismic crews based on their examination of several sites each December and January. The permits allow tundra travel for seismic camps when there is an average minimum of 15 cm (6 in.) of snow and 30 cm (12 in.) of frozen soil, which is determined by the number of times a hammer must strike a stake to drive it into the soil. Conditions are monitored throughout the winter. DNR closes tundra travel in April or May, again depending on conditions.

The only published study of seismic disturbance in relation to snow cover suggests that measurable, low-level disturbance occurs at depths of as much as 45 cm (18 in.) in tussock tundra, and 72 cm (28 in.) in sedge-shrub tundra (Felix and Raynolds 1989b). Moderate disturbance occurs at snow depths to 25 cm (10 in.) in tussock tundra and 35 cm (14 in.) in moist sedge-shrub tundra.

Knowledge of the distribution and ecological significance of snow in arctic ecosystems has grown considerably in the past 20 years (e.g., Jones et al. 2001, Liston 1999, Olsson et al. 2002, Sturm et al. 2001). The structure of the snowpack is critical to maintaining the relatively warm winter microclimate at the base of the snowpack (Pomeroy and Brun 2001). The subnivian layer, the highly porous granulated layer of snow at the base of the snowpack, acts as insulation and is important to many wintertime processes, such as soil microbial activity and wintertime carbon dioxide flux (Oechel et al. 1997), and to the movement of small mammals (Aitchison 2001). Plants are sensitive to the thermal conditions at the base of the snowpack (Walker et al. 2001a). Ice roads and pads and vehicle trails alter snowpack structure and can physically disturb vegetation and soils if the snowpack is thin.

Small amounts of snow in northern Alaska are a particular problem for wintertime exploration activities. Near the coast, the average April wind-packed snow depth is 30 cm (12

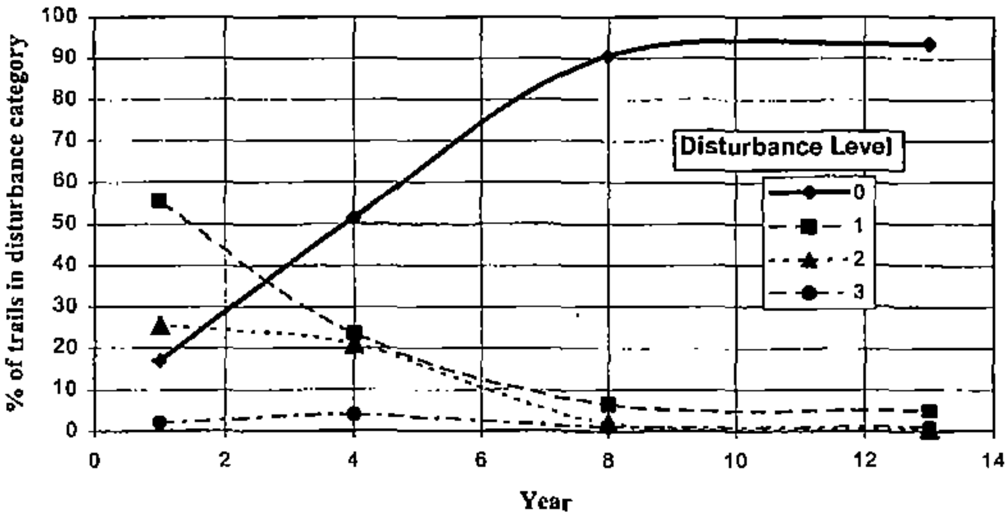
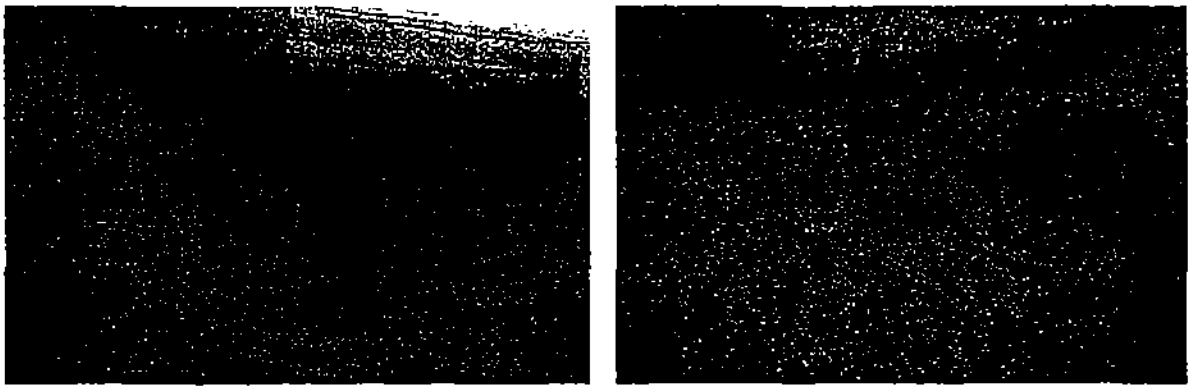


FIGURE 7-6. Recovery after seismic disturbance. Sources: Data from Felix et al. 1992, Emers et al. 1995, FWS 2002.

(a) (b)



(c)

FIGURE 7-7. Aerial views of seismic trails. (a) Intersecting seismic-exploration and camp-move trails, Arctic Foothills, 2001. The heaviest trail (center) near Kavik in the tussock tundra is a camp-move trail. The intersecting trails (left) are seismic lines. Also shown here are numerous stray trails that are not part of the camp-move or seismic trails. Tan colors show damaged cottongrass tussocks *(Eriophorum vaginatum)* and dead dwarf shrubs. Source: U.S. Fish and Wildlife Service. (b) Heavily impacted tundra in hill slope with frost boils, sedge-dwarf-shrub tundra, and high microrelief. Source: U.S. Fish and Wildlife Service. (c) Camp-move trail from 1985 exploration in the Arctic National Wildlife Refuge, photographed in 1994. This trail remained visible because of trail subsidence, a decrease in shrub and mosses, and an increase in standing dead sedge leaves. Source: Jorgenson et al. 1996.

in.). The snowpack normally builds up to about 20 cm (8 in.) within 10-20 days after freezeup and then increases slowly through the rest of the winter (Dingman et al. 1980). Several factors affect the local and regional distribution and characteristics of snow, including increasing snowfall from east to west and from north to south across the North Slope, gradients of wind across the North Slope, and differences in snow cover associated with topography. The use of average snowpack and frost thickness by regulatory agencies to determine when to open and close the tundra travel season does not consider such differences.

If snow cover increases in the future, as some climate-change models predict, the effects of seismic trails could be reduced. Snow cover also affects the depth of frost penetration. Generally, snow insulates the tundra, so if the snowpack accumulates earlier or to greater depths, the timing of the opening of the seismic season could be affected. Less snow would shorten the seismic season. Earlier warming in spring could mean the cessation of seismic activities earlier in the year. The length of the season for off-road tundra travel has decreased (Figure 7-8). The change in the off-road season is mainly the result of later opening dates for the season rather than earlier closing dates. A more complete understanding of just how much snow and frost penetration are needed to adequately protect the tundra from seismic operations is needed.

Potential Accumulation of Effects of Seismic Trails

According to the best estimate of the committee on the Cumulative Environmental Effects of Alaskan North Slope Oil and Gas Activities, 32,000 line miles of seismic trails, receiver trails, and camp-move trails were made between 1990 and 2001, and if current trends continue another 27,000 line miles will be surveyed in the next 10 years. A large percentage of the trails should recover within relatively short periods. Data from the Arctic National Wildlife Refuge showed that after 8 years only about 3% of the seismic and receiver line trails and 10% of camp-move trails were still disturbed (Emers et al. 1995).

Based on these recovery rates and modern ratios of trails in each disturbance category, the committee projected the total seismic line miles in each disturbance category into the future (Figure 7-9). This figure projects cumulative line miles of trails for the next 12 years in each of four disturbance level illustrated in Figure 7-5, and it assumes the same rates of recovery that occurred in the Arctic National Wildlife Refuge. According to this model, about 17,500 miles will recover fully (Level 0, although parts could be faintly visible from the air). About 6,200 miles will have Level 1 disturbance, 3,600 miles will have Level 2 disturbance, and about 300 miles will show Level 3 disturbance.

Although there are no comparable data for modern seismic methods, the Arctic National Wildlife Refuge data provide some useful insights. First, after about 6 years, the recovery of old trails in disturbance categories 1 and 2 about balance the addition of new trails. As long as the rate at which of new trails are added remains constant, the recovery of old trails generally keeps pace, and the total footprint of seismic trails on the landscape at any one time will remain about the same. The sum of trails in disturbance categories 1, 2, and 3 currently is about 10,000 line miles (Figure 7-9), so the posited relationship is valid only if the improved technology does not result in a decrease in the degree and amount of tundra disturbance. However, newer technologies appear to cause less long-term damage. There is a small increment of trails in disturbance category 3 that do not recover, and the total line miles in this category continues to climb slowly. Because of the large number of seismic line miles created each year, even very

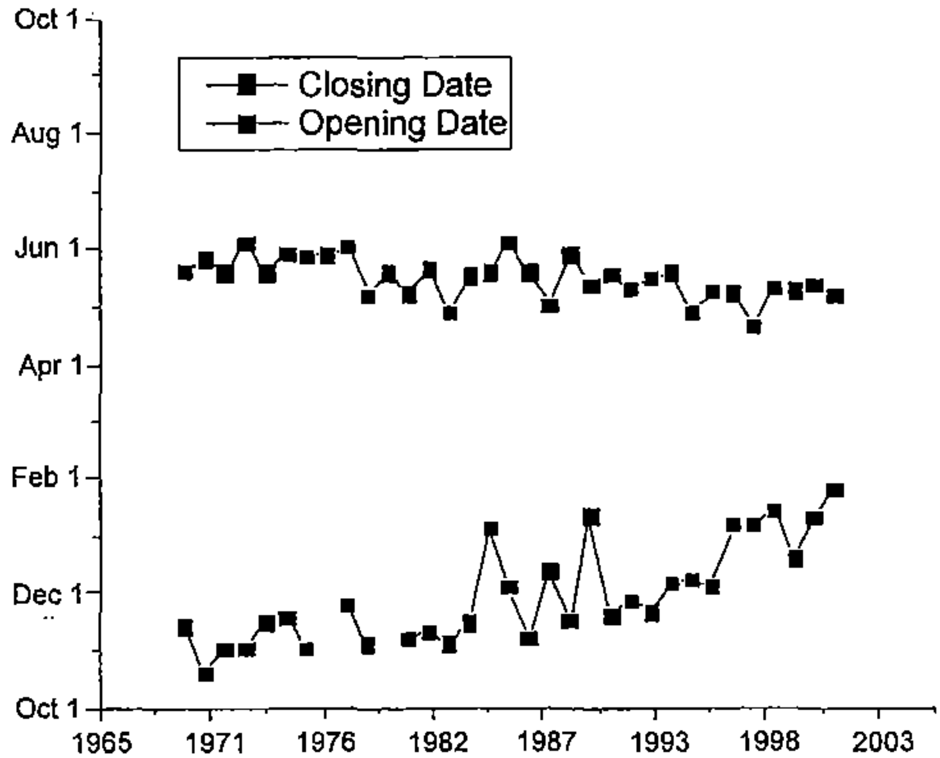


FIGURE 7-8. Opening and closing dates of North Slope off-road traffic. Source: Alaska Department of Natural Resources.

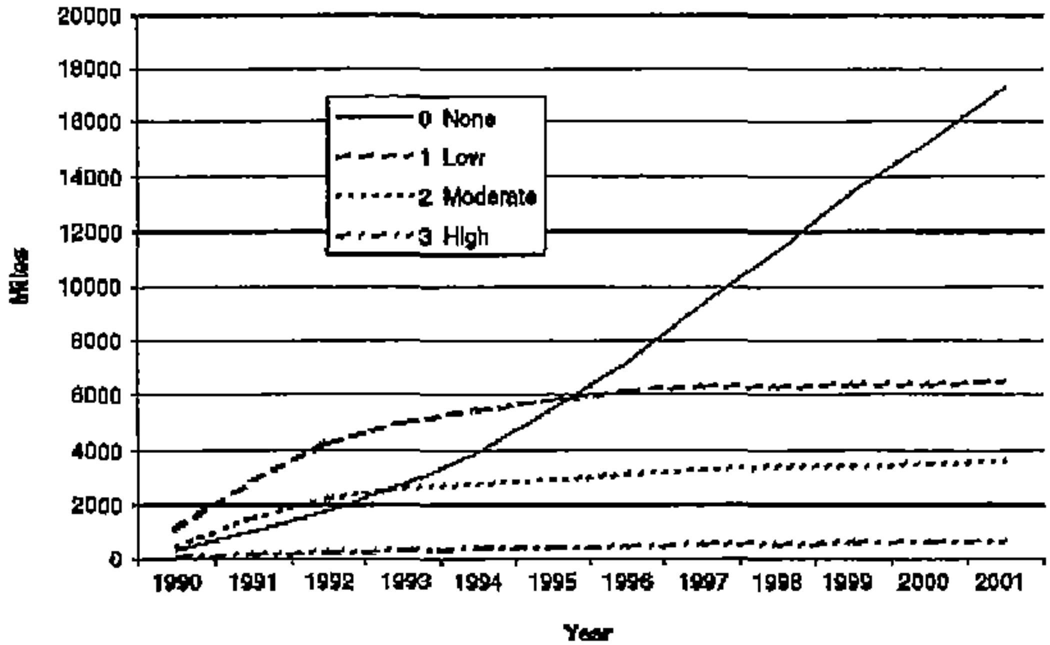


FIGURE 7-9. Hypothetical cumulative line miles of trails during 12 years and totals in the four disturbance levels based on the following: (1) Total seismic line miles equivalent to that during 1990-2001. (2) The ratios of line miles in each disturbance category is the same as that resulting from the 1984-1985 seismic surveys in the Arctic National Wildlife Refuge (Emers et al. 1995). (3) The recovery rate in each disturbance category is the same as that in the Arctic National Wildlife Refuge studies. Source: Alaska Geobotany Center, University of Alaska Fairbanks 2002.

small percentages of trails in category 3 can accumulate to large totals over many years. If this trend were to continue to 2025, then another 29,900 line miles will have been surveyed. If 1% of the trails are in category 3, this would add nearly 300 line miles of degraded land to the North Slope. Trails in this category can deteriorate over time and become worse as permafrost subsidence and erosion occur.

The model used here is based on information from studies that measured recovery rates on the ground. It does not address the question of how much remains visible from the air. About 15% of the trails created in the Arctic National Wildlife Refuge between 1984 and 1985 are still visible from the air (J. Jorgenson, FWS, unpublished, 2001). Those trails affect the visual quality of large landscapes and are a cause for particular concern in pristine areas, such as the Arctic National Wildlife Refuge, especially given that most North Slope travel is by small aircraft. There have been no studies to document recovery rates of trails visible from the air.

Some seismic trails have caused significant changes to plant communities (Emers and Jorgenson 1997, Emers et al. 1995). Although most trails recover to resemble the original plant community within about 8 years, heavily damaged areas do not. The long-term consequences of the changes are unknown, but possibilities include the establishment of weedy species and the subsidence of trails because of thermokarst. Invasive grasses have colonized some highly disturbed trails, making them more visible from the air (Emers et al. 1995).

An average of about 1,300 line miles of seismic trails is added each year. The total area likely to be affected annually can be estimated by multiplying by the width of trails—on average, 30 m (100 ft)—and adding the areas of the associated camp-move trails. This was done for the environmental impact statement for the northeastern portion of the National Petroleum Reserve-Alaska, in association with the first lease sale. Assuming the same ratio of 2-D to 3-D exploration for the entire North Slope, the predicted 13,000 line miles over 10 years would translate to a total affected area of 1,114-3,421 km^2 (430-1,321 mi^2). This estimate does not include areas affected by receiver lines perpendicular to main lines or to the many stray vehicle trails on the tundra. The estimate also does not include the areas between the trails, which often are visually affected, especially in areas of 3-D seismic exploration, nor does it include recovery that would occur within the 10-years period. It also does not address the fact that a good portion of the seismic line kilometers will occur in areas already surveyed using older seismic technologies. And it does not take recent technological improvements into account. But the estimate does give some impression of the extent of the areas that are likely to suffer effects caused by seismic activities in the near future, although the degree of effect is difficult to judge given that effects are less if the tundra is adequately protected by snow.

In the future, seismic-exploration is expected to increase in the foothills region, and effects are likely to be different from those documented on the coastal plain. Research will be needed to identify and monitor those effects. The committee is not aware of data that can be used to assess the ecological significance of the persistence of disturbed linear segments of tundra.

Ice Roads and Pads

Ice roads, airstrips, and drilling pads have been built in recent years to reduce costs and environmental effects of gravel construction (Hazen 1997, Johnson and Collins 1980). Extended-season ice pads have many environmental and economic advantages for exploration

(Hazen et al. 1994, Stanley and Hazen 1996). The ice pads are covered with reusable insulated panels that help preserve the ice in the summer, allowing drilling to resume nearly two months earlier the next season.

There have been some studies of the short-term ecosystem effects of ice roads (Johnson 1981, Johnson and Collins 1980, Walker et al. 1987a), but there have been no long-term studies. Most of the effects of ice roads involve the direct physical disturbance of vegetation, the effects of debris from the road, and destruction of the subnivian layer (Walker et al. 1987a). The biotic effects of ice roads are substantially less than those of gravel roads and pads but more severe than those of seismic trails. Studies of vegetation recovery at an extended-season ice drilling pad showed a 34% decrease in vascular plant cover 2 years after the pad melted; the effect was greatest on raised microsites (Noel and Pollard 1996). Climate warming could restrict the use of ice roads and pads in the future.

AIR QUALITY

The effects of air quality on vegetation near industrial facilities on the North Slope appear minimal: for example, concentrations of NO_x and SO_2 from 1989 to1994 were below those generally expected to be harmful to plants (Kohut et al. 1994). High concentrations of NO_x occurred only during a small percentage of monitored hours. The NO_x and SO_2 monitoring revealed no effects on vegetation that could be attributed to pollution. The researchers (Kohut et al. 1994) recommended continued monitoring at 2-year intervals to ensure that any changes in vegetation could be detected relatively quickly. This monitoring is not being conducted (Taylor 2001).

Lichens are known to be vulnerable to SO_2, and concentrations as low as 12 $\mu g/m^3$ for short periods can depress photosynthesis in several species, with damage occurring at 60 $\mu g/m^3$ (National Petroleum Reserve-Alaska FEIS IV(5)(b)(3)). (The National Ambient Air Quality Standards maximum 3-hr limit for SO_2 is 1,300 $\mu g/m^3$). Sensitivity of lichens to sulfates is greater under the moist and humid conditions that are common on the North Slope. Air monitoring that was conducted from 1989 to 1994 showed maximum 3-hr concentrations of SO_2 above 12 $\mu g/m^3$ at 11 of the 12 sites monitored; 1 site exhibited concentrations greater than 100 $\mu g/m^3$ (BLM 1999, Northstar FEIS Table 5.4-5). Thus, even though air quality meets national ambient-air-quality standards, it is not clear that those standards are sufficient to protect arctic vegetation.

Similarly, although most monitored concentrations of ozone were reported by Kohut and colleagues (1994) to be below those thought to injure temperate vegetation, little is known about the sensitivity of arctic vegetation to ozone.

The FWS has studied the effects of atmospheric deposition of contaminants on snowpack on the moss, *Hylcomium splendens*, at Prudhoe Bay and in the Arctic National Wildlife Refuge (FWS 1995a). The report documented enrichment of nutrients and several trace elements in the Prudhoe Bay snowpack compared with sites in the Arctic National Wildlife Refuge. "Significant inputs of major and trace elements, including heavy metals [were found] at Prudhoe Bay at two sites, one near drilling operations and the central processing facility, and the other near the North Slope Borough solid waste incineration facility." Effects appear to be local, however (FWS 1995a).

AREAS OF SPECIAL IMPORTANCE

Several features of the North Slope vegetation deserve special mention because they are important focal points for wildlife activity; nonacidic tundra, bird mounds, pingos, river corridors, salt marshes, and small groves of trees near springs.

Nonacidic Tundra Regions

Most North Slope oil and gas development has occurred on nonacidic tundra. Because it grows on mineral-rich soils, this tundra is especially important to wildlife. It is home to many plants and animals, including four major caribou herds, three of which calve in areas of coastal nonacidic tundra. The nonacidic soils of the region could contribute to this wildlife diversity (see Chapter 3 for additional discussion of soil pH). The digestible, nutrient-rich vegetation could be especially important for caribou and other herbivores. The warmer soils could provide habitat for burrowing mammals, such as voles (*Microtus oeconomus*), ground squirrels (*Spermophilus parryi*), and lemmings (*Lemmus sibiricus*), which in turn could provide favorable hunting grounds for a variety of predators.

River Corridors

River corridors are probably the most biologically diverse and the most affected of the important terrain types in the Prudhoe Bay region. A diversity of plant communities occurs in association with waterways: ground squirrels, bears, and foxes use well-drained valley sites for their dens, and all predators find abundant prey along rivers. Riparian systems vary considerably. For example, riparian communities are different in loess and sandy regions. Communities are more diverse in warmer portions of the North Slope.

Rivers were among the first areas disturbed by oil and gas development because they are sources of gravel and routes for roads and buried pipelines. The lower portion of the floodplain of the Little Putuligayuk River (Figure 7-10) has been intensively mined for gravel and used for waste disposal; in places, it is no longer recognizable as a floodplain (Walker 1995). Fluvial processes are slowed in the Arctic because the highest flows tend to occur when most of the floodplain is frozen. As a result, areas altered by gravel mining take much longer to recover than is the case in lower latitudes. Some components of river floodplains, such as higher terraces, are more sensitive to disturbance and also are slow to recover.

Pingos and Bird Mounds

Pingos, another important landform of the Arctic Coastal Plain ecosystem, attract numerous species of animals, including arctic foxes (*Alopex lagopus*), arctic ground squirrels, caribou, grizzly bears (*Ursus arctos*), lemmings, raptors, buff-breasted sandpipers (*Tryngite subruficollis*), plovers, and ptarmigan (M.D. Walker 1990, Walker et al. 1991). The pingos around Prudhoe Bay are apparently quite old, and they do not erode easily or collapse as do

FIGURE 7-10. Floodplain of the Little Putuligayuk River. Source: Alaska Geobotany Center, University of Alaska Fairbanks 2002.

pingos composed of more fine-grained materials, such as those in the Mackenzie River delta (Mackay 1979, Walker et al. 1985). They consequently have old, well-developed plant communities (M.D. Walker 1990, Walker et al. 1991). Pingos attract people because some animal species, such as arctic foxes, are easily trapped at these sites, and pingos offer good vantage point for hunters and surveyors. Most of the accessible pingos in the Prudhoe Bay region are littered with vehicle trails, trash, and debris from geodetic surveys; a few are scarred with bulldozer trenches formed during the search for gravel.

Bird mounds, which usually are less than 1 m high, are scattered abundantly across the flat coastal plain (Walker et al. 1980). They are thought to have accumulated organic matter over long periods from fertilization by birds and small mammals. Predatory birds use these higher sites to observe the surrounding terrain. Other animals, such as voles and lemmings, take advantage of the relatively dry habitats. The importance of bird mounds to coastal plain ecosystems has never been evaluated, but they support diverse plant communities. They are easily damaged by ice road construction and camp moves during seismic operations.

Rare and Endangered Plants

Three North Slope plant species are considered endangered or threatened by the Nature Conservancy as listed in the *Alaska Rare Plant Field Guide* (Lipkin and Murray 1997): *Erigeron muirii* (Muir's fleabane), *Mertensia drummondii* (Drummond's bluebell), and *Poa hartzii* var. *alaskana* (Hartz's bluegrass). All three occur in dry habitats associated with dry bluffs, flood plains, river terraces, sand dunes, rocky slopes, outcrops, fellfields, and mountain summits. Those habitats are the primary sources of ballast and fill used for construction projects.

FACILITY REMOVAL, REHABILITATION AND RESTORATION OF GRAVEL-COVERED AREAS

Many industrial activities and their accompanying accidents and consequences—spills or discharges of oil or other materials; tundra travel; the construction and operation of roads, airstrips, gravel islands and pads; gravel mining; dust deposition, and impoundments—disturb surface environments (Walker 1996). The extent to which effects accumulate depends in part on whether efforts are made to ameliorate them. The oil and gas industry generally defines *rehabilitation* as the conversion of a disturbed site into functional habitat for plants and animals without necessarily restoring the original species and processes. *Restoration* means the replacement of lost habitat features, species, and processes that were present prior to disturbance (AOGA 2001).

As noted in Chapter 4, the committee commissioned an analysis of the history of the North Slope road and infrastructure network (also see Appendix E). The analysis included an estimate of the area affected by industrial development judged to be *rehabilitated*. Rehabilitated areas as defined by Aeromap, Inc., included areas that were no longer definable as clearly disturbed in aerial photographs or areas that now provide functional habitat but might be different from the original. In most cases, these areas were not restored to their former condition. Rehabilitation to some degree has occurred on only about 195 acres—about 1%—of gravel pads.

The rehabilitated area includes the gravel mines of the Sagavanirktok and Kuparuk river floodplains rehabilitated by natural river action, engineered rehabilitation that occurred on abandoned exploration pads, and the flooding of the deep gravel mines in the oxbows of the Kuparuk River. According to the analysis, rehabilitation has occurred on about 11 ha (26 acres) of abandoned airstrips, 15 ha (37 acres) of offshore gravel pads, 29 ha (72 acres) of on-shore gravel pads, and 1,841 ha (4,549 acres) of gravel mines. Gravel has been removed from about 79 ha (195 acres); and the sites are in various stages of recovery. About 95% of the rehabilitation has occurred in gravel mine areas.

Some of the shallow gravel mines in the floodplains of the Kuparuk and Sagavanirktok rivers have been allowed to recover by the natural action of the rivers. Before mining, floodplains consisted of a mosaic of barren active channels and barren and vegetated islands. Numerous river bars and islands eliminated by mining have not been restored. The deeper gravel mines are not restored to their previous condition, but they are considered rehabilitated by Aeromap because they provide winter fish habitat even though they are strikingly different from the original habitat.

Although the size of the gravel footprint required to support operations has been greatly reduced (Streever 2000), relatively little progress has been made on restoring existing sites affected by gravel fill. Only about 1% of the roughly 3,733 hectares (9,225 acres) of tundra habitat on the North Slope covered by gravel roads, pads, airstrips, and other facilities, has been rehabilitated, either naturally or from revegetation efforts. The factors that contribute to the low rate of site restoration include technical and natural constraints imposed by the harsh environment of the North Slope; the lack of clear regulatory requirements governing the level and timing of restoration; uncertainty about whether currently unused sites will be required in the future; contamination and liability concerns; and the high cost of removing facilities and restoring sites in the region. Each of these issues is addressed below.

Technical and Natural Constraints

The North Slope presents special technical challenges to restoration and recovery. Extremely cold temperatures, meager precipitation (13-18 cm [5-7 in.] per year), and the short growing season lengthen recovery times substantially beyond those possible elsewhere in the United States. Natural recovery of disturbed sites to original soil and plant conditions has been estimated to require 600-800 years for upland mesic sites and 100-200 years for marsh sites (AOGA 2001).

Recovery of disturbed sites on the North Slope is complicated by the fact that any disturbance of the insulating vegetative mat can melt the underlying permafrost, a process that is extremely difficult to reverse and that can continue long after the initial disturbance ends. Finally, gravel pads and roads, which account for the vast majority of the directly affected habitat on the North Slope, retain moisture and nutrients poorly and so slow recovery processes.

Recovery times in the Arctic, as elsewhere, depend in part on the nature and extent of disturbance and the type of habitat affected. For example, wet sites tend to recover quickly from light oil spills; dry sites affected by diesel fuel spills recover exceedingly slowly, with little recovery occurring after several decades (Walker 1996). Disturbed areas that would recover relatively quickly in more temperate climates (such as those caused by Caterpillar tractor tracks), can persist for many decades because of melted permafrost.

Restoration Research

During the past few decades, considerable industry research has examined the feasibility of rehabilitating areas disturbed by oil-field activities (McKendrick 1997). Until recently, that work has focused on revegetating sites with exotic grasses to avert erosion. More recent efforts have focused on the use of native grasses and forbs and on the restoration of habitat processes and aesthetics, all of which are much more challenging goals (AOGA 2001).

A variety of rehabilitation strategies has been developed, including flooding of gravel mine sites to create overwintering habitat for fish; creation of wetlands in ponds perched on overburden stockpiles; revegetation of thick gravel fill and overburden to compensate for lost wildlife habitat; removal of gravel fill to help restore wet tundra habitats; restoration of tundra on less severely modified habitats; and remediation of areas contaminated by oil spills, seawater spills, and drilling mud (Jorgenson and Joyce 1994). The oil industry is conducting experiments at several sites throughout the Prudhoe Bay oil field and at old well sites in the National Petroleum Reserve-Alaska. Preliminary results indicate that, if cost is not a factor, a productive and diverse vegetative cover can be established even on sites with severe ecological limitations. Most of the studies suggest that natural recolonization occurs relatively rapidly on thin fill and on organic rich fill where moisture and nutrients are not severely limiting (Jorgenson 1997). Low temperatures near the coast, however, reduce the number of species available and the rate at which recolonization occurs. A survey of 12 revegetated pads in the National Petroleum Reserve-Alaska showed that on average only 3 native species were found on pads at the cold coastal sites, 10 were found on inland coastal plain pads, and 24 were found on relatively warm foothills sites (McKendrick 1987). Fertilization and seeding with nonnative species appears to delay natural recolonization (Jorgenson 1997).

More costly methods are required for rehabilitating the gravel roads, pads, and mine sites that dominate disturbed land (Jorgenson 1995). Construction of berms and basins, application of topsoil, and use of various plant cultivation techniques are required on these sites. However, only a very limited amount of topsoil has been stockpiled for future use in the oilfields (Jorgenson 1997). Sewage sludge is being considered as an alternative source of organic material. Native legumes with nitrogen-fixing ability could be essential for sustaining the long-term productivity of those sites.

Removal of gravel fill has recently been done in wetlands, and preliminary studies suggest that wetland mosaics of vegetation can be restored, although the method is expensive and finding acceptable locations for the fill can be difficult.

Gravel extracted from 24 open-pit gravel mines, (ADNR) affects some 2,580 ha (6,364 acres) in various floodplains and deltas on the North Slope (Table 4-4). Rehabilitation typically involves converting mine sites to lakes, with a channel usually cut between the pit and a stream or river so the site can be accessible to fish. Such sites create potential overwintering habitat for fish, but they also result in the permanent loss of the original habitats.

Restoration Standards and Requirements

Existing state and federal laws and regulations governing surface restoration lack clear definitions and standards, and they overlap in potentially conflicting ways. The lack of definitions in the relevant statutes and regulations of clear restoration goals makes it difficult to plan and design restoration activities.

The Federal 404 Program

Section 404 of the Clean Water Act authorizes the U.S. Army Corps of Engineers to issue permits for the discharge of any type of fill material into waters of the United States, including wetlands. Because virtually all of the Arctic Coastal Plain is in wetlands, permanent facilities (roads, pads) require Section 404 permits, as do causeways, gravel islands, gravel mines, pipeline burial routes, and other construction activities, regardless of location on state, federal, or privately held land.

Until 1979, however, the corps did not exercise its Section 404 authority on the North Slope, and it estimates that about half of the area covered by gravel was filled without permits (USACE 2001a). The corps now lacks jurisdiction over those "unpermitted" sites, and no detailed mapping or inventory of them exists (USACE 2001a,b). Since 1979, 1,179 permits have been issued on the North Slope (USACE 2001b,c); 3 have been denied (GAO 2002). The corps has no estimate of the total area affected by its Section 404 permits (USACE 2001b).

Restoration is not mandatory even for gravel roads, pads, and other facilities constructed under Section 404 permits. Restoration upon abandonment is governed by General Condition 2, one of the conditions included in all standard 404 permits, which states: "... Should you wish to cease to maintain the authorized activity or should you desire to abandon it without a good faith transfer, you must obtain a modification of this permit from this office, which *may* require restoration of the area" (emphasis added) (Army Standard Permit). The corps takes the position that the ultimate authority over restoration lies with the landowner (the state for state leases, the Bureau of Land Management [BLM] for the National Petroleum Reserve-Alaska leases, and the Minerals Management Service [MMS] for the Outer Continental Shelf [OCS] leases) (USACE 2001b). Fewer than 1% of the permits issued contain restoration requirements that are accompanied by specific success criteria, principally percentage cover required (USACE 2001b). The requirements do not define methods for estimating cover, specify whether cultivars or native species are to be used, or include specific monitoring methods to determine success (Streever 2000). As a result, different methods of defining percentage cover have yielded very different results (Streever 2000). The corps has reported that the most lenient requirement found in a review of permits for the North Slope—30% cover in 3 years—could not be met for gravel pads.

Recently, the corps has included ecosystem process goals in several of its permits for new facilities. For example, the Alpine permit requires that, upon abandonment, the gravel footprint is to be rehabilitated "in a manner that maximizes benefits to fish and wildlife resources, and restores the natural hydrology of the immediate project area footprint" (404 Permit #2-960874, Special Condition 9). However, specific standards for achieving those goals, criteria to measure performance, the timing of implementation, and the type and amount of monitoring required are not specified.

The corps has required gravel reuse as a special condition of particular permits. The Northwest Eileen permit (USACE permit 4-2000-0041) requires the permit holder to "remove and recover gravel" from 3 abandoned sites. This involves using gravel from existing pads, roads, and other unused facilities rather than mining new gravel and restoring the old sites. Gravel reuse has been required in only 6 permits issued by the corps (USACE 2001b). If gravel reuse is added as a special condition, the permit holder must arrange to have the gravel tested for hydrocarbon contamination and cleaned (by burning hydrocarbons off) if necessary. In the event that the contamination is too severe to be removed effectively removed, the permit holder must identify another site of equivalent size that could serve as a source of gravel. Gravel reuse and revegetation can be expensive, particularly if decontamination is required.

The nature, extent, and timing of restoration required by gravel reuse permits or upon ultimate abandonment is not specified in regulations and is subject to the discretion of the corps' Alaska District. In exercising that discretion, the corps does not appear to have made systematic use of the substantial research conducted by the industry and others on revegetation and restoration. Various experimental trials of different approaches to revegetation have been conducted by the industry at least since 1984. Those studies have yielded important information about the establishment of vegetation on gravel (Streever 2000).

Compensatory Mitigation

National policy and guidelines developed by the Environment Protection Agency (EPA) and the Army Corps of Engineers in 1990 under the Section 404 program require "compensatory mitigation" for the unavoidable destruction of wetlands that can be achieved by restoring existing degraded wetlands or by creating new, artificial wetlands. Because, the corps and EPA have taken the position that the North Slope is exempt from the compensatory mitigation requirement, however, the corps is not required to oblige companies to restore old oil-field sites as a condition of new permits—a strategy that has worked elsewhere to promote restoration.

Other Federal Restoration Requirements

In addition to the Section 404 permitting program, the federal government may impose additional restoration requirements in leases it awards on federal land. Under lease terms awarded in the National Petroleum Reserve-Alaska, no permanent facilities may be established in the exploration phase (National Petroleum Reserve-Alaska FEIS, Stip. # 27). To date, however, BLM has not developed specific dismantlement, removal, and restoration (DRR) requirements to meet its general goal of returning disturbed land to its original primary use (wildlife habitat and wilderness) (GAO 2002).[1]

On the federal OCS, MMS regulations, lease terms, and lease stipulations impose stringent requirements regarding removal of structures and plugging and abandoning wells. In most circumstances elsewhere in the United States, MMS has required platform removal and clearing of the ocean of obstructions to other uses (30 CFR Sec. 250.700); the agency has not specified requirements for abandonment of North Slope gravel islands.

[1] Lessees of land in the National Petroleum Reserve-Alaska are required by the lease terms to "reclaim the land as specified by lessor." The final environmental impact statement specifies no restoration requirements, and it explicitly leaves open the possibility that facilities may be left in place upon abandonment. NPRA FEIS, Stip #58: "Upon field abandonment or expiration of a lease or oil- and gas-related permit, all facilities shall be removed and sites rehabilitated to the satisfaction of the AO, in consultation with appropriate federal, State, and North Slope Borough regulatory and resource agencies. *The AO may determine that it is in the best interest of the public to retain some or all of the facilities.*" (emphasis added).

State Restoration Requirements Applicable to State Land

The Alaska Oil and Gas Conservation Commission (AOGCC) imposes stringent well-plugging and abandonment procedures for all wells throughout Alaska, regardless of land ownership. The Alaska DNR oversees activities affecting the surface (other than spills or other contamination, which is handled by the Alaska Department of Environmental Conservation [ADEC]).[2] Current state lease terms specify removal of all machinery, equipment, tools, and materials within 1 year of the expiration of a lease; older lease terms for most Prudhoe Bay leases allow lessees to leave behind infrastructure with state permission (GAO 2002). Older and newer leases alike leave decisions regarding the nature, timing, and extent of restoration of gravel roads, pads, and other facilities to an undetermined future process (ADNR):

> At the option of the state, all improvements such as roads, pads, and wells must either be abandoned and the sites rehabilitated by the lessee to the satisfaction of the state, or be left intact and the lessee absolved of all further responsibility as to their maintenance, repair, and eventual abandonment and rehabilitation.

Thus, as with the federal government, decisions regarding whether sites must be restored after abandonment and to what extent are largely left to future regulators.

Offshore, artificial islands in state waters have been abandoned under plans approved by DNR, which typically involve removing surface hardware, and debris, providing shore protection to a specific depth, and then allowing the island to erode naturally.

Under the existing unitization agreements approved by the State, nothing within a unit must be officially abandoned until the entire unit is closed. So, for example, even if the state were to decide to impose stringent restoration requirements, the companies are not obligated to implement them on any abandoned sites within the Prudhoe Bay oil field until the entire unit has been closed. The Army Corps of Engineers, however, can require rehabilitation of individual pads within a lease or unit, although it has done so in only a few instances.

Whether the oil companies have a clear, substantive obligation to remediate sites on the North Slope has been examined by a court of law on only one occasion (Exxon 2000). In that case, the Internal Revenue Service challenged Exxon's deduction of expenses related to future restoration. The court held that the standard language of the leases under which Exxon and other oil companies conduct activity in the Prudhoe Bay oil field did not create a clear obligation on the part of the oil companies to undertake restoration in the oil field, with the exception of specific well-plugging and abandonment requirements imposed by the AOGCC.

The almost 76,000 m^3 (100,000 yd^3) of solid waste generated by oil-field operations every year, includes scrap metal, waste insulation, tires, wrecked vehicles and airplanes, and old buildings. Although there have been improvements in waste management, large amounts of scrap have accumulated over time and there is no comprehensive plan for its disposition. At times, scrap is sent out on the return trips of barges that bring supplies to Prudhoe Bay, but often barges are sent back to Anchorage from the North Slope without a load of scrap. Already, the state is facing disposal of abandoned drilling rigs for which corporate dissolution, bankruptcies,

---

[2] Alaska statute AS46.03.822 makes owners and operators liable for "damages, for the costs of response, containment, removal, or remedial action" resulting from unpermitted release of hazardous substances. AS 46.03.826 defines hazardous substances to include oil and associated products and byproducts. The statute does not cover rehabilitation or restoration.

and mergers have clouded ownership (ADNR DPF 93-03), and the scrap issue is expected to become more serious as facilities age.

Local Government Restoration Requirements

The North Slope Borough has zoning authority that extends by ordinance to state, Native, and municipally owned land within the borough's boundaries. There is some debate over whether the borough's authority extends to federal land as well. The Coastal Zone Management Act requires consultation with the borough before leasing and development of federal land. The borough issues permits for most activities that affect the land surface. It may exercise its authority to require restoration of existing "orphan" sites (abandoned sites where ownership is unknown), of new-construction sites, or both as a condition of new permits. The committee found no evidence that the borough has exercised its authority to impose specific restoration requirements separately from those of other government agencies.

Local Native villages and corporations also control surface lands and subsurface mineral rights and can establish restoration requirements through contractual arrangements with the industry (GAO 2002).

Overlapping Authority

Because few restoration requirements have been imposed at the local, state, or federal level, overlapping jurisdiction among regulatory agencies has not been a major issue. However, as the fields age and as decisions about restoration begin to be made in earnest, the potential exists for inconsistent or contradictory restoration requirements applying to the same piece of land. For example, the Army Corps of Engineers, the state, and the North Slope Borough all have jurisdiction over activities on state land, and each is free to impose restoration requirements.

The lack of an effective, coordinated regulatory structure is partly to blame for the lack of significant progress in restoring disturbed North Slope sites. Without clear and specific standards, the industry faces significant uncertainty regarding what will and will not be acceptable to regulatory agencies. And without explicit time requirements and performance standards, there is little incentive for the industry to undertake expensive and complex restoration efforts. Finally, the absence of standards makes monitoring and enforcement difficult. In developing standards, flexibility must be built in to advance standards as restoration research advances.

Uncertainty Regarding Future Need for Sites

One obstacle to restoration and rehabilitation is uncertainty about whether old gravel roads, pads, airstrips, and other facilities might be needed in the future. As technology advances and the economics of production change, abandoned pads could become economically profitable to operate. Thus, there is some reluctance on the part of the industry to commit to restoring currently unused sites.

Contaminated Sites

The ADEC maintains a database of contaminated sites throughout the state. The database lists more than 90 contaminated sites associated with oil and gas activities on the North Slope. The extent and nature of contamination on those sites varies considerably.

As part of the charter agreement governing BP's acquisition of ARCO, the two companies agreed to assess and clean up 43 of their sites by the end of 2007 (Charter Agreement, II.A.3. and Exhibit D.2). BP and ARCO agreed to spend $10 million to assess and clean up another 14 orphan sites (Charter Agreement, II.A.1. and Exhibit D.1). ADEC confirmed that the 14 are the only known orphan sites, but that others are likely to be found (Judd Peterson, ADEC, personal communication, 11/13/01). The companies also agreed to work with ADEC to develop a database of contaminated and solid-waste orphan sites to identify the nature and location of the sites, the responsible parties, and the relative priority for cleanup of each based on an evaluation of risk to human health and the environment (State of Alaska et al. 1999).

Finally, as part of the charter agreement, ARCO and BP agreed to clean up 170 exploration and production reserve pits (Charter Agreement, Exhibit D.3.A. and D.3.B). This includes pits being cleaned out and closed pursuant to a 1993 consent agreement between environmental groups and ARCO. Another 158 pits in the area from the Canning River to Point Lay are being closed under the state's closeout regulations (J. Peterson, ADEC, personal communication, 2001). The contents of all production pits, and some exploration pits, are being ground and injected. The rest of the exploration pits are being closed using "freezeback," whereby below-grade pits are capped and allowed to freeze in place. One-hundred-eighty-four of the 328 reserve pits on the North Slope are now officially closed (ADEC 2002) but this does not necessarily mean that the sites have been restored. The fate of those sites, some of which could be affected by shoreline erosion, and of 5 "regional" drilling-waste disposal sites on the North Slope that used freezeback as the closure method is uncertain. Between 115,000 and 183,000 m^3 (150,000 and 240,000 yd^3) of waste was buried at each regional site (ADEC 2001a,b).

In addition to sites and reserve pits that are known to be contaminated, industry is concerned about the potential liability and expense associated with recycling possibly contaminated gravel from roads and pads. The ADEC has not studied the extent of contamination in gravel roads and pads (ADEC 2001b).

Economic Considerations

There have been no comprehensive estimates of the cost of dismantling and removing the roughly $50 billion worth of infrastructure installed over the past three decades on the North Slope or of restoring the thousands of square kilometers of tundra habitat affected by development (GAO 2002). Estimates for different projects indicate that the total cost will run into the billions of dollars.

Phillips Petroleum has estimated that it would cost between $50 million and $100 million to remove facilities and restore the Alpine area (Ryan 2001). With 30 million bbl (4.77 billion L, 1.26 billion gal) of oil produced to date, that cost is equivalent to $1.67–$3.33 per barrel. Alpine covers an area of 39 ha (97 acres) (MMS Liberty DPP Plan DEIS Table U.B-3), yielding an average restoration cost of between $1.2 million and $2.5 million per hectare ($500,000 and $1 million per acre). Assuming roughly similar costs to remove facilities and restore the estimated 3,600 ha (9,000 acres) of gravel-covered tundra on the North Slope, the overall cost of restoration could range from $4.5 billion to $9 billion.

In the context of litigation brought in 1989 and 1990, Exxon estimated that fieldwide costs to plug and abandon wells, dismantle and remove facilities, and close reserve pits using the freezeback method would be $928 million for the Prudhoe Bay field (not including gravel removal, revegetation, or grind-and-inject costs) (Exxon case 2000). The company calculated its share as $204 million. Exxon also estimated that well-plugging costs alone amounted to $132,000 per well (Exxon case 2000).

The Phillips 2000 *Annual Report* indicates that the estimated total future DRR costs stemming from its acquisition of ARCO Alaska amounted to more than $1.5 billion (Phillips 2000). Virtually all of Phillips holdings acquired from ARCO in Alaska are on the North Slope.

About 80 wells drilled on federal land in what is now the National Petroleum Reserve-Alaska were improperly plugged and abandoned, and some are leaking oil and other substances. The BLM estimates the cost to restore the sites at upwards of $100 million (GAO 2002).

The estimated cost to abandon two platforms in Cook Inlet is $31 million (VanDyke and Zobrist 2001).

The Army Corps of Engineers estimates that the average cost of gravel decontamination, reuse, and revegetation on the North Slope is approximately $2.5 million per hectare ($1 million per acre) of gravel picked up. With a total gravel footprint of 3,755 ha (9,225 acres) (see Chapter 4), the total cost is slightly more than $9 billion. However, that assumes that all the gravel would need decontamination, which is not the case.

The anticipated high cost of restoration on the North Slope raises concerns about whether adequate funds will be available to undertake restoration when production ceases. Most North Slope leases are now held by large, multinational, integrated oil and gas companies that clearly have the wherewithal to pay for abandonment and restoration.[3] However, if the North Slope follows the pattern exhibited by the rest of the industry in the United States, ownership is likely to change over time as production declines.

As large companies no longer find it economical to maintain leases, they could sell out to smaller companies with fewer expenses that can operate these leases profitably. A shift in ownership from large to small companies as fields age has already begun at Cook Inlet, where 14 of the 16 current offshore platforms began operations before 1969 (Van Dyke and Zobrist 2001). As production declined from 83 million bbl (13.2 billion L, 3.5 billion gal) per year in 1970 to 11 million bbl (2.75 million L, 462 million gal) per year in 1999, one large multinational company offered all of its Cook Inlet infrastructure for sale, and another sold 2 platforms to a much smaller independent business. A third sold its oil production facility to a smaller independent firm, although it retains its gas interest (Van Dyke and Zobrist 2001). A recent oil discovery in Cook Inlet has revived interest in the region.

If leases on the North Slope are transferred from the large multinational companies to smaller independent firms, the smaller concerns are less likely to have the resources to pay for restoration when production ceases. Existing state and federal bonding requirements are not remotely sufficient to cover the costs of restoration. The state DNR requires bonds of $500,000

[3] Following conventional accounting practices, the major companies that operate on the North Slope report amounts on their books that will be used for DRR. However, there is no actual money set aside for those purposes. DRR funds are, like depreciation, an accounting procedure, not actual cash accessible by subsequent leaseholders or government agencies.

per company statewide, whereas restoration of the Alpine oil field alone is estimated as $50 million to $100 million. The BLM requires bonds of $300,000 for the National Petroleum Reserve-Alaska, but the Army Corps of Engineers require no bonding for activities conducted under section 404 permits. Existing bond requirements also are intended to serve several purposes (among them to ensure royalty payments), further diluting the amount that would be available if needed for restoration.

The MMS bonding requirements are much higher: each company must have a $3 million statewide production bond. However, even this amount is sufficient to cover only a small fraction of estimated restoration costs. The MMS may require companies to post supplemental bonds equal to the estimated abandonment costs at the facility, but it has not yet done so on the North Slope.

The BLM, MMS, and DNR all specify that original lessees retain liability arising from activities that occurred before any lease transfer to other entities. In theory, this means original lessees would retain responsibility for restoration expenses.[4] However, it is not clear whether this will occur in practice. To date, there has been only one such transfer in Alaska, involving an offshore lease in Cook Inlet from a large multinational corporation to a smaller company. Because the multinational did not guarantee liability, the state raised the bond required of the new owner as a condition of the transfer (Van Dyke and Zobrist 2001). There are no formal criteria governing when additional financial assurances should be required (GAO 2002).

FINDINGS

Effects on Vegetation

- Effects of contaminant spills on North Slope vegetation have not accumulated because the spills have been small and cleanup and rehabilitation efforts at spill sites generally have been successful.
- Some 1,540 km (956 mi) of roads, 350 gravel pads, and the extensive gravel mining have combined to result in 7,011 ha (17,324 acres) of tundra and floodplains being directly covered by oil development. The total does not include the Trans-Alaska Pipeline and the Dalton Highway.
- Roads have had effects as far-reaching and complex as any physical component of the North Slope oil fields. In addition to covering tundra with gravel, indirect effects on vegetation are caused by dust, roadside flooding, thermokarst, and roadside snow accumulation. The effects accumulate and interact with effects of parallel pipelines and with off-road vehicle trails. The measurable direct effects covered approximately 4,300 ha (10,500 acres) in the developed fields, not including indirect of effects of the Dalton Highway.
- The indirect effects associated with roads, reducing roadside flooding, dust-killed tundra, and thermokarst, are estimated to cover at least 4,300 ha (10,500 acres). This does not include areas affected by off-road vehicle trails, including seismic trails.
- Dramatic progress has been made in minimizing the effects of new gravel fill by reducing the size of the gravel footprint required for many types of facilities and by substituting ice for gravel in some roads and pads.

[4] Transfer of Section 404 permits does not require Army Corps of Engineers approval. The new owner assumes the permit obligations of the permit holder upon transfer.

- Roadside dust has resulted in the loss of mosses and in earlier snow melt along many roads. Acidic tundra areas along the Dalton Highway with abundant *Sphagnum* moss are particularly sensitive to dust. Chip-seal treatment of roads could dramatically reduce generation of roadside dust.
- Impoundments next to raised roadbeds and pads have caused extensive habitat changes in flat portions of the Arctic Coastal Plain.
- Higher summer soil temperatures near roads and pads results in thermokarst, which is continuing to expand outward from roads.
- Some nonnative species were introduced in seed mixtures and mulches, but most have not persisted and have not spread beyond the sites where they were introduced.
- Networks of seismic trails (as well as ice roads and pads) cover extensive areas of the tundra. The proprietary nature of industry-obtained seismic data made it impossible for the committee to determine the total line kilometers and location of seismic trails for the full period of oil exploration on the North Slope. According to the committee's best estimate, more than 52,000 km (32,000 mi) of seismic trails, receiver trails, and camp-move trails were created between 1990 and 2001, an annual average of 4,700 km (2,900 mi). The committee views seismic trails as producing a serious accumulating visual effect. The significance of ecological effects on vegetation of large areas of the North Slope is unclear.

About 96 % of trails from the 1984-1985 seismic exploration of the Arctic National Wildlife Refuge were not noticeable on the ground after 8 years of recovery, but an estimated 15 % of those trails are still visible from the air after 16 years of recovery. This would be a major concern for proposed future exploration in areas of high wilderness value if similar effects occurred.

- Data from the FWS provide good information regarding the long-term recovery from 2-D seismic exploration on trails that were created 15 years ago. However, the results might not be applicable to the high spatial density of the newer trails and larger camps associated with 3-D surveys. It is open to conjecture whether the continuing evolution in the technology of seismic-data acquisition would reduce effects.
- Current regulations require minimum average snow depth and frost penetration of 15 cm (6 in.) and 30 cm (12 in.), respectively, before seismic activities are permitted on the tundra. Those requirements are not based on scientific evidence. The variations in snow depth and density across the North Slope are not considered in the establishment of opening dates for seismic exploration each year, and 15 cm (6 in.) of snow is not sufficient to protect the tundra in many areas of the North Slope.
- The use of ice roads and ice pads has increased and will continue, but little information is available on how long effects will persist after one or more seasons pass.
- Because the hundreds of onshore spills that occur annually are well reported, they have been the subject of a great deal of concern among North Slope residents and others. However, because most spills have been small, have occurred on gravel pads, and have been cleaned up, the ecological effects of onshore spills have been small and localized and hence have not accumulated. However, such spills contaminate gravel, which impedes its reuse for environmental reasons (and adds liability and financial issues.)
- There have been no documented negative effects of air quality to vegetation in the Prudhoe Bay region, but the potential exists for local, long-term, effects of air pollutants on some types of vegetation, particularly lichens, to accumulate.

Areas of Special Concern

- Several North Slope landscape features are focal points of plant and animal diversity, including pingos, riparian corridors, salt marshes, and small groves of trees.
- The role of the coastal nonacidic tundra regions for wildlife has not been adequately studied.
- None of the three rare plant species found on the North Slope is threatened by current oil-field activities, although all occur in habitats that could be mined for gravel.

Facility Removal and Restoration

- Tundra sensitivity to disturbance, recovery from disturbance, and the effectiveness of rehabilitation techniques are all affected by local variations in climate, soils, and topography.
- The oil industry and the regulatory agencies have made strides in developing techniques for rehabilitating some disturbed habitats. The most difficult areas to reclaim contain the 3,736 ha (9,225 acres) covered by gravel roads and pads. Some of those are still in use. Only about 1% of that area has been rehabilitated.
- Liability for contaminated sites poses an obstacle to the reuse of gravel.
- State, federal, and local government agencies have largely deferred decisions regarding the nature and extent of restoration (with the exception of well-plugging and abandonment procedures). The lack of clear state or federal performance criteria, standards, and monitoring methods governing restoration is partly to blame for the lack of significant progress in restoring disturbed sites on the North Slope.
- Because the obligation to restore abandoned sites is unclear and because the financial capacity to do so uncertain, the committee judges it unlikely that most disturbed habitat on the North Slope will actually be restored unless those constraints change.
- Comprehensive restoration and landuse planning for the post-oil-and-gas era on the North Slope is lacking.
- No funds have been set aside for dismantling and removing the estimated $50 billion worth of existing infrastructure on the North Slope or for restoring the thousands of hectares of tundra affected by industrial activities. Total costs are likely to be billions of dollars.

RECOMMENDATIONS

Effects on Vegetation

- Long-term studies of the response of tundra plant communities to a variety of contaminants, including oil, diesel fuel, and saltwater, would promote the development of contaminant sensitivity and recovery potential maps.
- Changes in roadside thermokarst over time should be documented and monitored to determine long-term trends in the expansion of those areas.
- Studies are needed to determine the amount of snow and frost penetration required to protect tundra from the effects of seismic exploration. Some plant species are particularly sensitive to seismic trails, so the studies should consider effects at the plant-species level.

- Monitoring of the long- and short-term effects of off-road ice roads and other off-road trails is needed.
- An inexpensive monitoring program focused on lichens should document trends in the accumulation and effects of sulfur and other air pollutants on vegetation.

Areas of Special Concern

- Ecosystem and wildlife studies on the North Slope would benefit from spatial databases that include more detailed information on substrate chemistry, climate, and topography.
- A multiple-scale planning procedure is needed to identify areas of special botanical and wildlife concern, such as riparian systems, nonacidic tundra, coastal wetlands, and pingos, at regional, landscape, and plot-specific scales.

Facility Removal and Restoration

- A comprehensive, slopewide plan should be developed to identify landuse goals after the oil industry leaves. The plan should specify the rehabilitation and restoration objectives needed to achieve the goals, identify specific performance criteria and monitoring requirements tied to rehabilitation and restoration objectives, provide an inventory of facilities on the North Slope and information on ownership, identify contamination status and former habitat type, and discuss whether portions of the site might be likely to have future uses. It should include a mechanism to ensure that adequate financial resources will be available to restore public lands in accordance with the plan.
- Site-specific plans for eventual revegetation should be developed for each developed site, taking into account regional climate, substrate, and topographic setting.

8

Effects on Animals

Animals can be affected directly by oil and gas activities or indirectly via alterations in habitat or food supplies. At sea, animals can be affected by noise, particularly sounds generated by seismic exploration, and by spills of oil and other contaminants. On land, animals can be affected by noise associated with seismic exploration, routine industrial activities, vehicle and aircraft traffic, and disturbance of dens. In addition, animals can be indirectly affected by changes in vegetation caused by industrial activities, contaminant spills, withdrawal of water from lakes and streams, and by the availability of anthropogenic food sources. For obvious reasons, attention has been directed toward animal species such as whales, seals, fish, bears, caribou, and birds that have particular economic, esthetic, or cultural value. Most invertebrates and many smaller vertebrates have not been studied. A review of the fates and effects of oil in the sea (NRC 2003) details much recent information.

POPULATION DYNAMICS

Terrestrial animals are mobile as adults. They can move away from sources of disturbance or find new habitat. Declining populations in areas where local extinction is a danger, can be replenished by the immigration of individuals from other areas. The movements of individual animals, however, make it difficult to assess the effects of industrial activities on the North Slope. Data are needed on the behavior of individual animals and on trends over larger areas than are required, for example, to assess effects of road dust on plants.

Although many studies have examined the responses of various species on the North Slope to roads, ground and aerial traffic, gravel pads, pipelines, and impoundments, for example, it is difficult to assess the implications of the findings for the long-term population dynamics of those species. Rarely are data available with which to compare the quality of the lost or disrupted habitats with that of remaining, undisturbed habitats. There are only inadequate estimates of the total fraction of high-quality habitats affected by commercial activities.

To guide its thinking about effects of industrial activities on animals, the committee on the Cumulative Environmental Effects of Alaskan North Slope Oil and Gas Activities used basic principles and concepts of population ecology. One process of central importance is habitat selection (Cody 1985). All animals select habitats for various activities (breeding, molting, hibernating) using clues associated with the suitability of habitats for those activities. Because individuals that make good habitat choices reproduce more successfully than those that make poor choices, populations evolve so that individuals prefer to be in habitats that best serve their needs. Thus, individual animals select the regions containing the best, on average, available habitats (Rosenzweig 1981), and use poorer habitats only when better habitats are fully occupied or when the density of individuals in the better habitats is high enough to lower expected success below levels attainable in poorer habitats. At a landscape scale, animals travel to regions that maximize long-term productivity, although in a particular year, those regions might not be the best (Griffith et al. 2002).

Biologists can use habitat selection behavior as an indicator of habitat quality. For example, because some species of waterfowl travel long distances after completing reproduction to molt in particular areas on the North Slope, we can assume that those are the best available molting areas and that their loss would force individuals to molt in less favorable places. Similarly, if caribou typically calve in specific areas, we can assume that those are the best available calving areas. Although data might not be available about the likely suitability of other areas—to which individuals might be displaced—it is prudent to assume that alternative areas are less desirable than the ones currently used.

When patterns of habitat occupancy are constrained by behavioral dominance or population density, a population is likely to have "source-sink population dynamics" (Hanski and Gilpin 1997), which result when reproductive rates are higher than death rates in high-quality habitats. The better habitats are sources of emigrants that disperse into and occupy poorer quality habitats (sink habitats), in which death rates exceed birth rates. Population densities can be quite high in sink habitats even though persistence of the species in those habitats depends on a regular supply of immigrants from source habitats.

An important consequence of source-sink population dynamics is that a substantial proportion of the population of a species can be found in sink habitats. Without detailed demographic data, distinguishing between source and sink habitats can be difficult at best (Pulliam 1988). Loss of source habitats could threaten the viability of a population even though most of the habitat occupied by the species in a region remains relatively intact. Thus, as activities and structures associated with oil and gas development expand into the National Petroleum Reserve-Alaska and into the foothills of the Brooks Range, the result could be an unexpected decline of species even though total habitat loss might be modest. In predicting the effects of expanded activity on the North Slope, the committee attempted to identify those species and areas where source-sink population dynamics are likely to be operating and used the available information to evaluate the likelihood that source-sink dynamics would occur. Although all receptors were considered from this point of view, source-sink dynamics was discussed only for those that appeared to be affected by it.

MARINE MAMMALS

Although primary productivity is low in the freshwater and marine ecosystems of northern Alaska, it is enough to support many species of carnivorous vertebrates. The marine mammal fauna off northern Alaska consists of three truly arctic species: ringed seal (*Phoca hispida*), bearded seal (*Erignathus barbatus*), and polar bear (*Ursus maritimus*) and four subarctic species: spotted seal (*Phoca largha*), walrus (*Odobenus rosmarus*), beluga whale (*Delphinapterus leucas*), and bowhead whale (*Balaena mysticetus*) that move into the area seasonally from the Bering and Chukchi seas (Ferrero et al. 2000, Frost and Lowry 1984, Lentfer 1988). Beluga whales spend most of their time in the Beaufort Sea in deep offshore waters.

Bowhead Whales

The bowhead whale is large—up to 18 m (60 ft) long. It is a baleen whale that once was common in northern circumpolar waters. Massive exploitation by commercial whalers greatly reduced its numbers to the current five small groups in the Bering Sea, Okhotsk Sea, Spitzbergen, Davis Strait, and the Hudson Bay (Shelden and Rugh 1995).

The Bering Sea stock is found seasonally in the Bering, Chukchi, and Beaufort seas and in parts of the East Siberian Sea. For many centuries bowhead whales have been important nutritionally and culturally to the coastal Native people of western and northern Alaska (Inupiat), the Chukotka Peninsula (Inupiat and Chukchi) of the Russian Far East, and northwestern Canada (Inuit) (for example, see Krupnik 1987, Sheehan 1995, Stoker and Krupnik 1993). This stock was heavily exploited by commercial whalers beginning in 1848 and ending in about 1914 (Woodby and Botkin 1993). Before commercial whaling, the population is estimated to have been between 14,000 and 26,000 (Breiwick et al. 1981) with estimates of 22,000 animals having been taken (Shelden and Rugh 1995). By the end of the commercial whaling period it is thought that only a few thousand remained.

As a result of the 1993 census effort conducted off Point Barrow, Alaska, the Bering Strait stock of bowhead whales is estimated at 8,200 (95% estimation interval from 7,200 to 9,400) (Raftery and Zeh 1998). The estimated annual rate of increase from 1978 to 1993 was 3.2% with 95% confidence interval 1.4% to 5.1%. As described in Chapter 1, accurate censuses of bowhead whales were accepted only after long efforts by Alaska Native hunters to correct earlier work.

The Bering Sea stock of bowhead whales spends the winter (from about late November to about mid-March) in the Bering Sea primarily at or near the ice edge. In the spring, most bowheads move north from the vicinity of Saint Lawrence Island, along the Alaskan coast to Point Barrow and then eastward, with most reaching the Canadian part of the Beaufort Sea by early to mid-June (Shelden and Rugh 1995). Although many spring migrants move in newly forming open areas (leads) in the ice, bowheads also move through ice-covered seas (Clark and Ellison 1988, 1989; Clark et al. 1996), often breaking through ice (to at least 15 cm [6 in.]) to breathe (George et al. 1989). Most spend the summer in the Canadian part of the Beaufort Sea. During fall, (late August to mid-October), they migrate westward through the Alaskan part of the Beaufort Sea, then into the northern part of the Chukchi Sea, and then south along the Chukotka coast. Most return to the Bering Sea by mid-November.

Bowhead whales depend heavily on euphausiids and copepods (Carroll et al. 1987, Lowry 1993, Lowry and Burns 1980, Lowry and Frost 1984, Lowry et al. 2001), small prey (3-4 cm [1-2 in.]). Bowheads feed throughout the year, at least to some extent. There are inadequate data to properly evaluate the importance of the Alaskan portion of the Beaufort Sea as feeding habitat for bowhead whales, especially during their fall migration. Because this is the time when they are susceptible to disturbance by the noise of exploration for oil, the information is needed for a full assessment of the effects of noise on bowheads.

It probably takes about two decades for a bowhead to achieve sexual maturity. Conception likely occurs in late winter or early spring, and calves are usually born during the spring migration (Kenney et al. 1981; Koski et al. 1993; Rugh et al. 1992; Shelden and Rugh 1995; Tarpley et al. 1983, 1999; Tarpley and Hillmann 1999). Bowheads can live 100 years or more (George et al. 1995, 1999).

Oil- and Gas-Related Activities and Bowhead Whales

The activities most likely to affect bowhead whales are marine seismic exploration, exploratory drilling, ship and aircraft traffic, discharges into the water, dredging and island construction, and production drilling. To date there have been documented effects of industrial noise. As was true of early censuses, the current understanding of the effects of noise on bowheads was achieved only after long efforts of Alaska Native hunters to correct early, imperfect studies (Chapter 1). There have been no major offshore oil spills on the North Slope.

Marine seismic exploration produces the loudest industrial noise in the bowhead whale habitat. Some seismic surveys are conducted in winter and spring on the sea ice, but most are done in the summer-autumn open-water period. Thus, bowheads and seismic boats are in the same areas during the westward fall migration. In the nearshore Alaskan Beaufort Sea, nearly all the fall-migrating bowhead whales avoided an area within 20 km (12 mi) of an operating vessel, and deflection of the whales began at up to 35 km (21 mi) from the vessel (Richardson 1997, 1998, 1999; NMFS 2002). Noise levels received by these whales at 20 km (12 mi) were 117-135 dB (NMFS 2002).

Disturbance to fall migrating bowhead whales also has been shown in relation to offshore drilling in the Alaskan Beaufort Sea. At the 1992 Kuvlum site the approaching fall-migrating whales began to deflect to the north at a distance of 32 km (19 mi) east of the drilling platform and bowhead calling rates peaked at about the same distance (Brewer et al. 1993). At the 1993 Kuvlum #3 site the whales were nearly excluded from an area within 20 km (12 mi) of the drilling platform (Davies 1997, Hall et al. 1994).

During the 1986 open-water drilling operations at the Hammerhead site, no whales were detected closer than 9.5 km (6 mi) from the drillship, few were seen closer than 15 km (9 mi), and one whale was observed for 6.8 hours as it swam in an arc of about 25 km (15 mi) around the drillship (LGL and Greeneridge 1987). The zone of avoidance therefore seemed to extend 15-25 km (9-15 mi) from the drillship. Acoustic studies done at the same time provided received levels of drillship noise that can be related to the zone of avoidance. At 15 km (9 mi) from the 1986 Corona, site received sound was generally 105-125 dB (LGL and Greeneridge 1987); at 11 km (6 mi) from Hammerhead, received sound was generally 105-130 dB.

Estimating Future Accumulation of Effects

Industrial Noise

If oil- and gas-related activities continue in the Alaskan waters of the Beaufort Sea, the major noise will be generated with marine seismic exploration. Other significant noise will continue to be produced by exploratory and production drilling, island construction, and vessel transit. The probable consequences are diversion of animals from their normal migratory path, possibly into areas of increased ice cover, and less use of the fall migration corridor as feeding habitat.

If two or more types of disturbance occur at the same time or in the same general area, the effects could be greater than those observed from single sources. The greatest diversion would occur if two or more seismic vessels operated simultaneously with one just offshore of the other.

Such a disturbing influence set across the migratory path could displace the whales seaward into areas where ice conditions are more dangerous for hunters, prevent some whales from passing, reduce use of the area as feeding habitat, and affect the other behavior in the animals.

Spilled Oil

There are no data on Arctic oil spills and bowheads because no major oil spill has occurred in the Beaufort Sea. However, the potential for an oil spill and its likely effects on bowhead whales are viewed by bowhead-dependent hunters as the greatest threat to the whale population and to their cultural relationship with the animal (Ahmaogak 1985, 1986, 1989; Albert 1990). Oil spilled in broken-ice cannot be cleaned up effectively, and it is expected that whales would not avoid oil-fouled waters.

Each environmental impact statement (EIS) relating to industrial activity in the Beaufort Sea contains estimates of the likelihood of an oil spill. For example, the final EIS for Beaufort Sea Planning Area Oil and Gas Lease Sale 170 (MMS 1998 IV-A-12) estimated a 46-70% chance of a spill of 1,000 barrels (bbl) or more. Increasing industrial activity in the Beaufort Sea, coupled with existing production at the Endicott and Northstar facilities, would lead to rising probability of a significant oil spill.

The *Exxon Valdez* experience shows that cleaning up spilled oil is difficult, even in ideal conditions in ice-free waters (Loughlin 1994). An oil spill would be most difficult to control during periods of broken ice—in the fall when bowheads migrate through the area. During this period, new ice is forming, slush ice is often present, ice is in the form of chunks and pans, and ice formed earlier can move into the area with the drifting and shifting ice pack. Mechanical recovery alone would likely be able to clean up only a small fraction of oil in broken ice (ADEC 2000).

An oil spill would pose less risk to bowhead whales if the whales could detect spilled oil and avoid it. Although there is no direct evidence about how bowhead whales would react to oil-fouled waters, Dall's porpoise, harbor porpoise, killer whales, and grey whales moved through waters contaminated by the *Exxon Valdez* accident (Harvey and Dahlheim 1994). Also, fin, humpback, and probably right whales did not avoid an oil spill off Cape Cod, Massachusetts (Goodale et al. 1981, cited in BLM 1982). Bowhead whales regularly surface in slush ice, and easily break through thin ice to breathe, so they are unlikely to avoid surfacing in oil-covered waters. The toxic effects that inhalation of oil vapors and ingestion of oil on bowhead whales would probably be similar to those described for seals and polar bears, below.

A modest amount of attention has been devoted to studying the likely effects of spilled oil on bowheads (for example, see Albert 1981b, Hansen 1985 and Beaufort-Sea-related EISs). One method compares the structure of the various tissues of the whale that are most likely to contact the oil with those of better-studied mammals. Related studies of the bowhead, begun in the late 1970s with examination of subsistence harvested whales and with the collection and examination of tissues from those whales (Albert 1981a, Kelley and Laursen 1980), indicated that the skin, the eyes, the baleen, and the lining of the gastrointestinal tract of bowhead whales are likely to be injured by contact with spilled oil (Albert 1981b).

The Skin

The skin of a bowhead whale is 10-22 mm (0.4-0.9 in.) thick over much of its body (Haldiman et al. 1981, 1985, 1986). Although bowheads have the soft, smooth skin typical of most cetaceans, they also have dozens to hundreds of roughened areas (1-4 cm [0.4-1.6 in.] diameter) of skin surface (Albert 1981b, Haldiman et al. 1985, Henk and Mullan 1996) the cause of which is not yet known (see Figure 8-1). In some of the roughened areas, the epidermal cells between the epidermal rods have been removed. The exposed epidermal rods then appear as tiny hairlike or filamentous projections. The great increase in exposed surface (microrelief) of these roughened areas increases the area to which oil can adhere. In a laboratory experiment, oil adhered, in proportion to the roughness of the skin surface, to formalin-preserved bowhead skin exposed to crude oil on water (Haldiman et al. 1981). The roughened areas of skin had large numbers of diatoms and bacteria, including potential pathogens with varying tissue-destructive enzymes (Shotts et al. 1990). Thus, it is likely that oil contact would be harmful.

The Eyes

The conjunctival sac associated with the eye is so extensive that an adult human's fingers can pass beneath the eyelids and reach approximately two-thirds of the way around the eye (Albert 1981b, Dubielzig and Aguirre 1981, Haldiman et al. 1986). Thus, a large surface exists for an irritant (such as spilled oil) to contact sensitive visual structures (Zhu 1996, 1998; Zhu et al. 2000, 2001).

The Baleen

Bowheads filter prey from the water with their extensive baleen apparatus (Lambertsen et al. 1989). Many of the hair-like filaments that form the margin of the baleen plates break off during feeding and are commonly found in the stomachs of harvested bowheads. Because the bowhead's baleen apparatus is so extensive and the filaments on the margin of each plate are so prominent, the baleen would be fouled if a whale fed in oiled waters (Albert 1981b, Braithwaite 1980, 1983).

A laboratory study (Braithwaite et al. 1983) showed that crude oil strongly adhered to isolated bowhead baleen and interfered with filtration efficiency for approximately 30 days. Less of an effect on filtration was found on isolated baleen (fin, sei, humpback, gray whale) characterized by short, rather stiff bristles (Geraci 1990, Geraci and St. Aubin 1982, 1985). Petroleum also had little direct effect on isolated baleen from several whale species (St. Aubin et al. 1984). A bowhead probably could filter out the heavier portions of spilled oil, including globules and "tar balls," and would probably swallow the oily material and the dislodged oiled baleen filaments along with its prey.

The Stomach

Broken-off baleen bristles swallowed during feeding can form "tangles" in the stomachs of bowheads (George et al. 1988). Those dislodged bristles could combine in the stomach with weathered oil components (such as tar balls) to form a sticky mass (Albert 1981b).

The stomach of the bowhead whale consists of four chambers, one of which is a narrow channel that connects two other larger chambers (Tarpley 1985; Tarpley et al. 1983, 1987). Blockage, leading to gastric obstruction, could occur in this small, narrow connecting channel, which has small entrance and exit openings, if a bowhead fed in oil-fouled waters (Albert 1981b). Ingested oil would also have toxic effects whose severity would be related to the amount of oil swallowed.

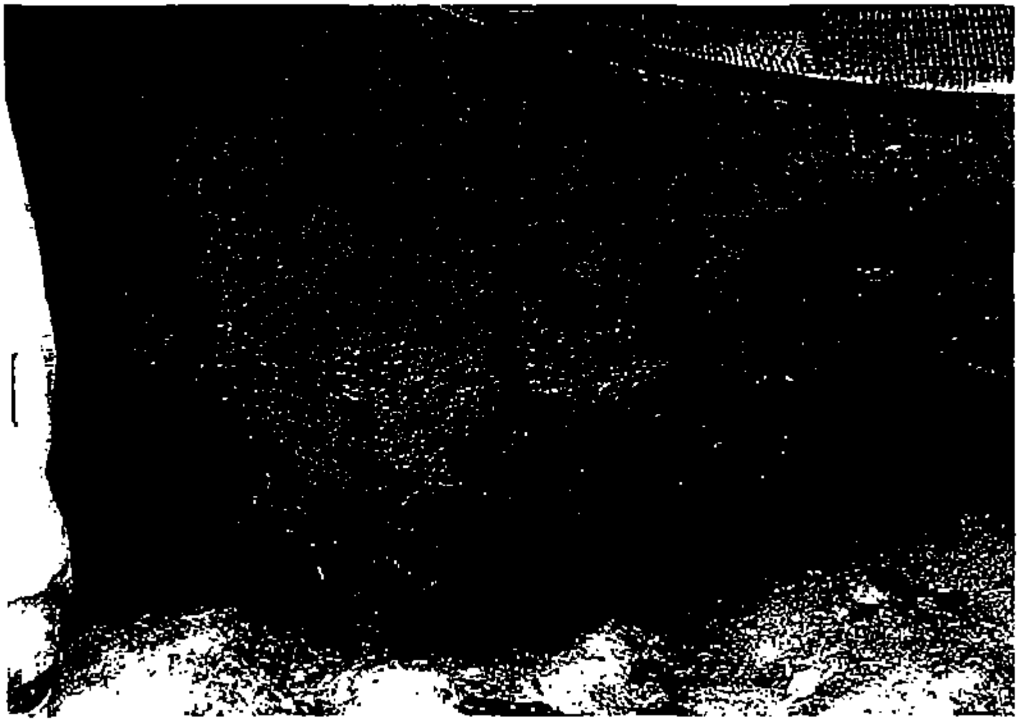


FIGURE 8-1. Subsistence harvested bowhead whale, on the ice at Barrow. This photo shows a portion of the left side of the head. The blowhole area is in contact with ice (near knife). A portion of left row of baleen is visible in the upper right of the photo. Note the large number of lesions (arrows) on the skin surface. These commonly seen eroded areas make the skin surface much rougher than in unaffected areas. A section of skin with lesions (upper right of photo) was removed from the skin of the upper jaw.

Findings

- Noise from exploratory drilling and marine seismic exploration causes fall-migrating bowhead whales to divert around noise sources, including drillship operations and operating
- seismic vessels, at distances of 15-20 km (9-12 mi).
- In view of the large zone of near total avoidance around a single operating seismic vessel, if more than one such vessel is operating in the Alaskan portion of the Beaufort Sea when fall-migrating bowheads are in those waters, the diversion of migrating whales could be much increased.
- Data needed for an improved assessment of the effects of seismic noise was delayed for many years due to overreliance on a study that underestimated such effects, and because of inadequate consideration given to relevant observations by subsistence hunters.
- Available data are inadequate regarding the full effects of industrial noise (seismic noise in particular) on fall-migrating bowhead whales in the Alaskan portion of the Beaufort Sea.
- There are inadequate data regarding the importance of the Alaskan portion of the Beaufort Sea as feeding habitat for the bowhead whale, especially during the fall migration.
- Harm to marine mammals from contact with spilled oil (as in the *Exxon Valdez* experience and other instances) and specific morphological characteristics of the bowhead whale (eroded areas of skin, extent of conjunctival sac, narrowness of stomach-connecting channel) indicate that spilled oil would pose a great potential threat to those organs in bowhead whales.

Recommendations

- Studies should determine the distance from an operating seismic vessel (and received noise at that distance) at which the "average" bowhead whale begins to deflect, begins to change its rate or type of vocalization, reaches the point of greatest deflection, and returns to the normal migration path. Studies also should examine the effects of multiple noise sources in different configurations.
- Studies should determine the extent to which bowhead whales make use of the Alaskan portion of the Beaufort Sea as feeding habitat.
- The use of sound to divert whales from a spill site and prevent them from contacting spilled oil should be investigated.

Seals and Polar Bears

In Alaska, spotted seals, bearded seals, and walrus spend most of their time in the Bering and Chukchi seas and generally use only the westernmost part of the waters off the Alaska North Slope. Ringed seals and polar bears are common in waters off the North Slope where oil and gas exploration and development have occurred. The main areas of concern with regard to effects on those animals from oil and gas activities are the potential for contamination (reviewed by Geraci and St. Aubin 1990) and for disturbance caused by industrial noise in the air and water (reviewed by Richardson et al. 1995).

The effects of industrial activity on marine mammals in the North Slope have been difficult to measure. Clearly, spilled oil can be toxic to marine mammals (Geraci and St. Aubin

1990, Loughlin 1994, NRC 2003), although there have been no major spills in the Beaufort Sea, or in any similar arctic environment, so no field data exist that can be used to evaluate or predict consequences. Observations and studies of responses of marine mammals to noise are difficult to interpret (Richardson et al. 1995); nevertheless, it is clear that noise can cause pronounced behavioral reactions and displacement of some species. However, it has not been possible to predict the type and magnitude of responses to the variety of disturbances caused by oil and gas operations, or, most important, to evaluate the potential effects on populations. Whether there are effects on the biology of the affected marine mammal species, displacement of animals could have important consequences for Alaska Natives seeking to harvest those animals for subsistence.

Hunting and Other Deaths Caused by Humans

Before the Marine Mammal Protection Act (MMPA) became law in 1972, active sport hunting for polar bears off western and northern Alaska reduced that population (Amstrup et al. 1986). Since then, marine mammals may be hunted only for subsistence and handicraft purposes by Alaska Natives, and there are no federally imposed limits on that hunting unless populations are declared depleted. Since 1988, hunting of polar bears from the southern Beaufort Sea stock has been controlled by a conservation agreement between the Inupiat of northern Alaska and Inuvialuit of the western Canadian Arctic who hunt a shared population (Nageak et al. 1991); the number of animals taken each year is well documented. From 1988 to 1995 the average annual take of 58.8 bears was well below the estimated "potential biological removal level" of 73 (FWS 1998) and therefore was considered safe.

Little is known about the number of ringed seals harvested, but they are an important subsistence resource to indigenous people throughout the Arctic (Smith et al. 1991). Alaska Native dependence on, and interest in, hunting marine mammals is influenced by many factors, including cultural involvement, employment, community wealth, logistics, and ice and weather conditions. The number of animals killed by hunters can be expected to vary accordingly. However, current legal restrictions should prevent harm to populations of these animals if they are properly enforced.

Marine mammals also are killed in other ways. At least one ringed seal pup has been killed by a bulldozer that was clearing seismic lines on shore-fast ice of the Beaufort Sea. A polar bear died on the North Slope apparently after eating a container of dye used to mark temporary airstrips (Amstrup et al. 1989). It is not uncommon for residents to shoot polar bears in defense of life and property, both in coastal communities and at industrial facilities. Two polar bears were killed in this manner along the Beaufort Sea coast in 1990 and 1993, one at the Stinson oil exploration site and the other at Oliktok Point (Scott Schliebe, FWS, personal communication). Regulatory agencies and the oil and gas industry have made serious efforts to minimize interactions with polar bears, both to increase human safety and to safeguard the bears (Truett 1993).

Oil

Laboratory experiments in which three polar bears were coated with crude oil showed dramatic effects (Øristland et al. 1981). Oil ingested during grooming caused liver and kidney damage. One bear died 26 days after oiling and another was euthanized. Stirling (1990) detailed numerous behavioral characteristics and ecological considerations that suggest that polar bears are especially susceptible to oil contamination. Laboratory experiments also have been done to determine the effects of oiling on ringed seals (Englehardt et al. 1977). After 24 h in a pen with oil-covered water, ringed seals' blood and tissues showed evidence of hydrocarbons that had been incorporated through inhalation, and kidney and liver damage. In another study (Geraci and Smith 1976), three seals died within 71 minutes after oil was put into their pool, presumably because of a combination of hydrocarbon inhalation and stress. Data presented by St. Aubin (1990a) described the various ways that pinnipeds could be affected by oil, much of it confirmed by studies of effects of the *Exxon Valdez* oil spill on harbor seals (Frost et al. 1994a,b; Lowry et al. 1994; Spraker et al. 1994; NRC 2003). However, as far as is known, neither ringed seals nor polar bears have been affected by oil spilled as a result of North Slope industrial activities.

Noise

Most of the effort to describe the effects of noise and disturbance on marine mammals has been devoted to studies of bowhead whales. However, pinnipeds also react to a variety of disturbances, such as noise from aircraft and ocean vessels (Richardson et al. 1995). Some studies of the potential effects of disturbance on shore-fast ice on pupping ringed seals have been done. Those studies showed that there was probably some displacement of ringed seals from areas close to artificial islands in the central Beaufort Sea (Frost and Lowry 1988), and that there was a higher abandonment rate of seal breathing holes close to seismic survey lines (Kelly et al. 1988). Noise probably affects haulout behavior of pinnipeds but no quantitative data are available. From data collected in the central Beaufort Sea from 1985 to 1987, Frost and colleagues (1988) concluded that there were no broad-scale effects of industrial activity on ringed seals that could be measured by aerial surveys, but they also noted that there was little offshore activity during those years. Subsequent industry-funded monitoring studies for the Northstar and Liberty projects suggested minor effects on ringed seals from ice road construction and seismic exploration (Harris et al. 2001, Richardson and Williams 2000). For most of the year, polar bears are not very sensitive to noise or other human disturbances (Amstrup 1993, Richardson et al. 1995). However, pregnant females and those with newborn cubs in maternity dens both on land and on sea ice are sensitive to noise and vehicular traffic (Amstrup and Gardner 1994). Seismic exploration has disturbed a bear in a maternity den (FWS 1986). Current regulations require industry to avoid polar bear dens as much as possible (FWS 1995b).

Habitat Changes

Human activities in, on, and adjacent to sea ice can cause habitat changes that affect marine mammals. In winter, ringed seals maintain holes in the shore-fast ice, and they give birth to their pups in lairs under the snow in spring (Smith and Stirling 1975). If the thickness of the ice, the amount and distribution of snow cover, or the timing and characteristics of breakup change, seal productivity or survival will be reduced (Furgal et al. 1996, Smith and Harwood 2001). Polar bears can be attracted to artificial structures that create leads in the ice because the leads increase the area bears use to hunt ringed seals. Buildings also offer places for bears to forage for human discards and stimulate their curiosity (Stirling 1988a). Not only does this increase the likelihood that bears will encounter contaminants, but it also increases the chances they will need to be driven away or killed to protect human safety. Ice breaking, especially in areas of shore-fast ice, obviously would result in major changes to habitat, with likely effects on ringed seals and polar bears.

In waters off the North Slope, ringed seals feed principally on arctic cod, euphausiids, and amphipods (Lowry et al. 1980). Those species, along with bowhead whales, copepods, and seabirds, form a relatively simple pelagic trophic system with some obvious potential for competitive interactions (Frost and Lowry 1984). Ringed seals are the primary prey of polar bears (Smith 1980, Stirling 1988b). Changes in population sizes of any of these species, either natural or caused by humans, could affect other components of the ecosystem.

For polar bears, mark-recapture studies in the Beaufort Sea suggest that the population increased considerably between 1967 and 1998 (Amstrup et al. 2001), probably because hunting has been limited (Amstrup et al. 1986). Ringed seals are harder to count. Efforts to develop a program to monitor ringed seals in the Beaufort Sea region began in 1985-1987 and continued in 1996-1999. Analysis of data from 1970 to 1987 (Frost et al. 1988) suggested the density of hauled-out seals fluctuated considerably from a high of 3.5 seals per km^2 (9.1 seals per mi^2) to a low of 1.1 seals per km^2 (2.6 seals per mi^2). Results of more recent surveys are being analyzed (Frost et al. in prep). Neither assessment program is sensitive enough to detect the substantial changes in population size that would be expected to result from oil and gas exploration and development and other human activities. However, because so far the marine waters of the Beaufort Sea have seen only limited and sporadic industrial activity, it is likely that there have been no serious effects or accumulation of effects on ringed seals or polar bears.

Permitting Incidental Take

The Marine Mammal Protection Act prohibits the taking of marine mammals—including polar bears and ringed seals—except in specifically permitted circumstances. The MMPA allows the secretary of commerce to permit industrial operations (including oil and gas exploration and development) to take small numbers of marine mammals, provided that doing so has a negligible effect on the species and will not reduce the availability of the species for subsistence use by Alaska Natives. Regulations governing the permits identify permissible methods, means to minimize harm, and requirements for monitoring and reporting. The permits have been used to minimize the effects of on-ice activities on pupping ringed seals, to require planning and personnel training that minimizes conflicts with polar bears, and to provide buffer zones around known polar bear maternal den sites.

Potential for Accumulation of Effects

No formal projections have been made of how likely effects on ringed seals or polar bears from future oil and gas activities are to accumulate with effects of other human activities, although the U.S. Fish and Wildlife Service (FWS) has produced a useful review of current and future threats to polar bears and their habitats (FWS 1995b). For purposes of making such a projection, the committee's scenario assumes that offshore exploration for oil and gas, and possible extraction, will occur in the Beaufort Sea from Barrow to Flaxman Island, and possibly to the Canadian border. Activity would occur mostly near shore, adjacent to onshore oil reserves, and development would entail methods and structures similar to those currently in use (gravel islands or bottom-founded structures, horizontal drilling, buried pipelines, and an emphasis on working during winter).

Full-scale industrialization of near-shore areas would most likely result in at least partial displacement of ringed seals. The frequency with which polar bears come into contact with people and structures is undoubtedly a function of the amount of activity in their habitats. Even with the best possible mitigation measures in place, it is certain that some bears will be harassed or killed. More human activity along the coast and near shore could reduce the suitability of some areas for use by denning female bears. This effect is likely to be greatest east of the Canning River, especially within the 1002 Area of the Arctic National Wildlife Refuge, where the highest concentration of on-land dens is found (Amstrup 1993, Amstrup and Gardner 1994). Efforts to identify areas where polar bears are most likely to den in the eastern part of the North Slope (Durner et al. 2001), should improve the ability of regulators and industry to reduce disturbance of denned bears.

Contact with spilled oil or other contaminants in the ocean would harm ringed seals and polar bears, and the likelihood of spills would increase with increased exploration and development. Amstrup and colleagues (2000) modeled the spread of a hypothetical 5,900 bbl (939,000 L, 248,000 gal) oil spill from the Liberty prospect[1] as it might affect the seasonal distribution and abundance of polar bears in the Beaufort Sea. The number of bears potentially affected by such a spill ranged from 0 to 25 with summer open-water conditions and 0 to 61 with autumn broken-ice conditions. In its findings permitting the oil and gas industry to take polar bears in Alaska waters, the FWS stated, "We conclude that if an oil spill were to occur during the fall or spring broken-ice periods, a significant impact to polar bears could occur" (Federal Register 65:16833). It seems likely that an oil spill would affect ringed seals the same way the *Exxon Valdez* affected harbor seals (*Phoca vitulina*) (Frost et al. 1994a, Lowry et al. 1994, Spraker et al. 1994), and the number of animals killed would depend largely on the season and the size of the spill. Polar bears could be further affected if they ate oil-contaminated seals (St. Aubin 1990b).

Climate change also will affect marine mammals (Tynan and DeMaster 1997). Sea ice is important in the life of all marine mammals in the arctic and subarctic regions (Fay 1974). Already, there have been dramatic decreases in the extent and thickness of sea ice throughout the northern hemisphere, and those trends are expected to continue through the next century (Vinnikov et al. 1999, Weller 2000). The distribution, abundance, and productivity of Alaskan marine mammal populations will likely be altered by the combined effects of changes in physical habitats, prey populations, and inter-species interactions (Lowry 2000). Warming is likely to

[1] The Liberty prospect is not being developed as of late 2002.

increase the occurrence and residence times of subarctic species (spotted seals, walrus, beluga whales, bowhead whales) in the region.

Negative effects on populations of truly arctic species (polar bears, ringed seals, and bearded seals) are likely to result from climate warming. Polar bears and ringed seals depend on sea ice, and reductions in the extent and persistence of ice in the Beaufort Sea will almost certainly have negative effects on their populations (FWS 1995b). Climate change has already affected polar bears in western Hudson Bay, where bears hunt ringed seals on the sea ice from November to July and spend the open-water season on shore where they feed little. In a long-term study, Stirling and colleagues (1999) documented decreased body condition and reproductive performance in bears that correlated with a trend toward earlier breakup of sea ice in recent years. The earlier breakup gives bears a shorter feeding season. They are leaner when they come ashore, and they must fast longer. Many ringed seals give birth to and care for their pups on stable shore-fast ice, and changes in the extent and stability or the timing of breakup of the ice could reduce productivity (Smith and Harwood 2001). Because of the close predator-prey relationship between polar bears and ringed seals, decreases in ringed seal abundance can be expected to cause declines in polar bear populations (Stirling and Øritsland 1995).

How these independent factors might combine to influence populations cannot be predicted with current knowledge. If climate warming and substantial oil spills did not occur, cumulative effects on ringed seals and polar bears in the next 25 years would likely be minor and not accumulate.

Currently there are no research plans or studies that specifically address potential accumulating effects on polar bears or ringed seals off the North Slope. Unless such studies are designed, funded, and conducted over long periods (decades) it will be impossible to verify whether the effects occur, to measure their magnitude, or to explain their causes.

Findings

- Industrial activity in marine waters of the Beaufort Sea has been limited and sporadic and likely has not caused serious cumulative effects on ringed seals or polar bears.
- Careful mitigation can help to reduce the effects of North Slope oil and gas development and their accumulation, especially if there is no major oil spill. However, the effects of full-scale industrial development of the waters off the North Slope would accumulate through displacement of polar bears and ringed seals from their habitats, increased mortality, and decreased reproductive success.
- A major Beaufort Sea oil spill would have major effects on polar bears and ringed seals.
- Climate warming at predicted rates in the Beaufort Sea region is likely to have serious consequences for ringed seals and polar bears, and those effects will accumulate with the effects of oil and gas activities in the region.
- Unless studies to address potential accumulation of effects on North Slope polar bears or ringed seals are designed, funded, and conducted over long periods, it will be impossible to verify whether such effects occur, to measure them, or to explain their causes.

CARIBOU

Introduction

The effects of North Slope industrial development on barren-ground caribou (*Rangifer tarandus granti*) herds have been contentious. Although much research has been conducted on caribou in the region, researchers have disagreed over the interpretation and relative importance of some data and how serious data gaps are. The disagreements are especially significant because caribou are nutritionally and culturally important to North Slope residents and because caribou are widely recognized as important symbols of the state and well-being of North Slope environments. For these reasons, the committee assembled information on caribou and evaluated conflicting interpretations of the information about how oil and gas development might have affected their population dynamics. The committee's consensus on effects to date, and projections of probable future effects, is the product of this careful analysis and deliberation.

Assessing the effects of oil and gas development on caribou is not straightforward because many factors other than oil and gas activities affect the sizes of North Slope caribou herds—changes in weather vegetation, disease, and predators, for example. Therefore, there is no steady baseline against which to identify and assess disturbance-induced changes. To evaluate the effects of petroleum development on caribou, the committee examined changes in distribution and habitat use, and evaluated the nutritional and reproductive implications of those changes and how they altered population dynamics.

Background

Caribou are ubiquitous on the North Slope. Four separate herds, ranging nearly 20-fold in size, are recognized on the basis of distinctly different calving grounds (Skoog 1968, Figure 8-2). The extent of seasonal migration varies with herd size (Bergerud 1979, Fancy et al. 1989, Skoog 1968). By far the largest is the Western Arctic Herd (WAH), estimated at 460,000 (in 2001). It calves in the Utukok uplands south of Barrow and summers throughout the North Slope and Brooks Range west of the Colville River, including most of the National Petroleum Reserve-Alaska. Wintering areas include both the western North Slope and the southern foothills of the Brooks Range. The annual range of the Teshekpuk Lake Herd (TLH), numbering 27,000 (in 1999), lies within the WAH summer range. Calving and summer ranges are in the coastal zone near Teshekpuk Lake; the winter range typically is confined to the coastal plain and nearby foothills. Estimated at 123,000 (in 2001), the Porcupine Caribou Herd (PCH) calves on the coastal plain and lower uplands in northeastern Alaska within the Arctic National Wildlife Refuge and adjacent Yukon Territory. During the summer, the PCH ranges throughout much of the eastern North Slope and Brooks Range; its wintering areas include the Ogilvie and Richardson mountains in western Canada and the southern Brooks Range in eastern Alaska. At 27,000 (in 2000), the Central Arctic Herd (CAH) is distributed primarily within state lands between the Colville and Canning rivers. CAH calving and summer ranges are on the coastal plain, and the winter range typically extends southward into the northern foothills of the Brooks Range. During the past 27 years, the size of the PCH has been nearly constant; the other three herds have increased substantially (Figure 8-3).

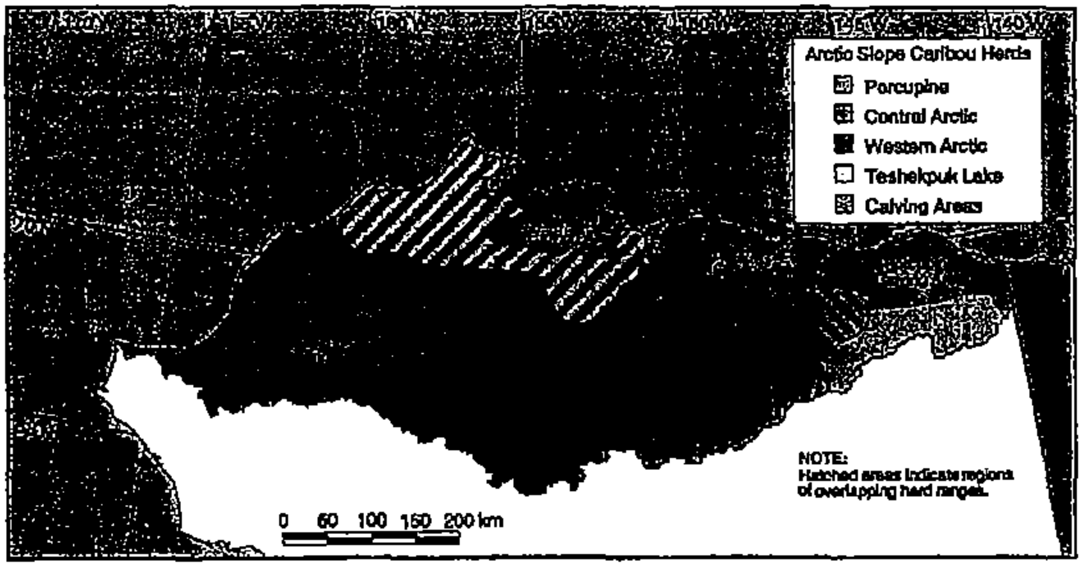


FIGURE 8-2. Arctic Caribou Herds. Source: Alaska Geobotany Center, University of Alaska Fairbanks 2002.

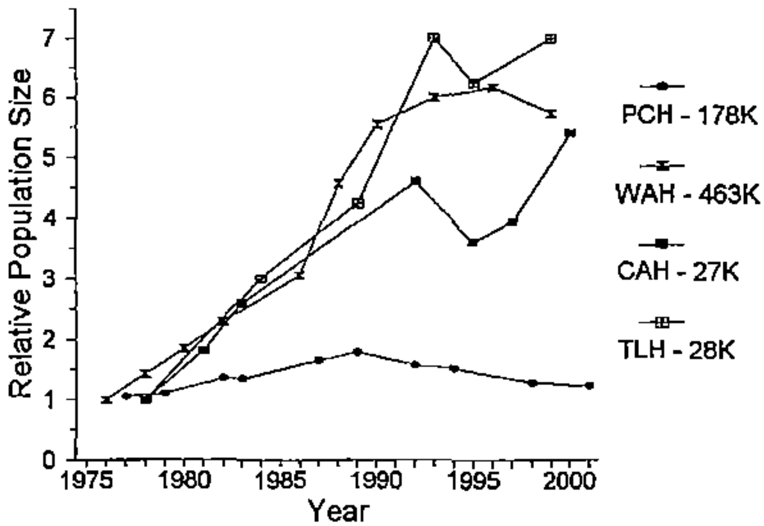


FIGURE 8-3. Relative post-calving herd sizes (minimum observed = 1.0) of the 4 Alaska barren-ground caribou herds (PCH = Porcupine caribou herd; WAH = Western Arctic herd, CAH = Central Arctic herd; TLH = Teshekpuk Lake herd), 1976-2001. Maximum observed population size for each herd is noted in the legend. Source: Griffith et al. 2002.

Central Arctic Herd

For the past 50 or 60 years, all four herds (Figure 8-2) have been exposed to oil and gas exploration activity, but only the CAH has been in regular and direct contact with surface development related to oil production and transport. Its calving ground and summer range lie within the oil-field region near Prudhoe Bay; its autumn, winter, and spring ranges encompass the Dalton Highway (also called the Haul Road) and the area around the Trans-Alaska Pipeline (Cameron and Whitten 1979b). The CAH has increased from around 5,000 animals in the late 1970s to its current (2000) size of 27,000 (Figure 8-3).

Parturient females, along with most nonparturient females and yearlings, arrive on the coastal calving ground in mid-May (Gavin 1978, Smith et al. 1994). The exact timing depends on patterns of snowfall and snowmelt (Cameron et al. 1992, Gavin 1978). Most calving occurs within 50 km (31 mi) of the Beaufort Sea (Whitten and Cameron 1985, Wolfe 2000). Virtually all calves are born between late May and early June (Cameron et al. 1993) within two or three calving concentration areas (Whitten and Cameron 1985, Wolfe 2000). At the landscape level, selection and repeated use of a calving ground is probably related to both the distribution of predators, which are less abundant on the coastal plain (Rausch 1953; Reynolds 1979; Shideler and Hechtel 2000; Stephenson 1979; Young et al. 1992, 2002), and the likelihood of favorable foraging conditions (Griffith et al. 2002). Annual shifts in concentrated calving within the overall calving ground are driven by spatial changes in the quality and quantity of new forage, principally sedges (Bishop and Cameron 1990, Wolfe 2000). An additional advantage of coastal calving is proximity to "insect-relief habitat," which eliminates the need for extensive travel with a young calf.

Bulls and the remaining noncalving females and subadults, which stay inland during the calving period, follow the northward progression of plant growth (Whitten and Cameron 1980), arriving on the coastal plain in late June (Cameron and Whitten 1979, Gavin 1978). The midsummer diet includes a variety of deciduous plants (Roby 1978; Trudell and White 1981; White and Trudell 1979, 1980; White et al. 1975, 1981).

Insects substantially affect nutrient balance by reducing food intake and by increasing energy expenditure. Mosquitoes are present from late June through late July (White et al. 1975, Russell 1976, Dau 1986). On warm, calm days, when mosquitoes are active, caribou move rapidly to cooler, windier areas on or near the coast, returning inland to preferred feeding areas when harassment abates (Cameron and Whitten 1979, Cameron et al. 1995, Child 1973, Dau 1986, Roby 1978, White et al. 1975). These movements appear to optimize foraging opportunity relative to energy expenditure (Russell 1976, Russell et al. 1993, Walsh et al. 1992, White et al. 1975). Oestrid flies (warbles and nose bots) emerge in mid-July and persist through early August (Dau 1986). When oestrids are active, caribou stand head-down or run erratically (Dau 1986, Nixon 1990, Roby 1978). This behavior probably reduces larval infestation, but it increases activity and reduces feeding time at the expense of nutrient balance (Helle and Tarvainen 1984, Murphy and Curatolo 1987, Russell et al. 1993).

By autumn, caribou move inland (Cameron and Whitten 1979a), and breeding occurs from late September through mid-October, while enroute to the winter range. Most of the CAH winters in the foothills and mountainous terrain of the northern Brooks Range, although a few caribou typically remain on the coastal plain year round (Cameron and Whitten 1979b, Cameron et al. 1979, White et al. 1975). Lichens, which are low in protein, predominate in the winter and spring diets (Roby 1978).

Ecological Strategies

During June and July, caribou body energy and nutrient reserves are low (Chan-McLeod et al. 1999, Gerhart et al. 1996), and parturient and maternal females attempt to maximize their intake of high-quality forage (Klein 1970, Kuropat 1984, Kuropat and Bryant 1979, Russell et al. 1993, White et al. 1975). They replenish body protein reserves mobilized during late gestation (Gerhart et al. 1996) and attempt to meet or exceed the metabolic demands of lactation (White et al. 1975, 1981), which are highest during the first 3 weeks postpartum (Chan-McLeod et al. 1999, White and Luick 1984). The benefits of good nutrition include increased growth rates (Allaye-Chan 1991, White 1992) and survival of calves (Haukioja and Salovaara 1978). Good nutrition is enhances summer weight gain of a female and increases the probability that she will conceive in autumn (Adams and Dale 1998; Cameron and Ver Hoef 1994; Cameron et al. 1993, 2000; Dauphiné 1976; Eloranta and Nieminen 1986; Gerhart et al. 1997b; Lenvik et al. 1988; Reimers 1983; Thomas 1982; Thomas and Kiliaan 1998; White 1983).

The intake of high quality forage often is reduced by adverse weather. A late spring snowfall or late snowmelt decreases forage quality and availability, resulting in lower birth weight (Adamczewski et al. 1987, Bergerud 1975, Eloranta and Nieminen 1986, Espmark 1979, Reimers 2002, Rognmo et al. 1983, Skogland 1984, Varo and Varo 1971) and delayed parturition (Cameron et al. 1993; Skogland 1983, 1984), both of which reduce survival of offspring (Adamczewski et al. 1987, Eloranta and Nieminen 1986, Haukioja and Salovaara 1978, Rognmo et al. 1983, Skogland 1984). From late June through early August, repeated and often severe insect harassment reduces the frequency and duration of both suckling (Thomson 1977) and foraging bouts (Helle et al. 1992, Mórschel and Klein 1997, Russell et al. 1993, Toupin et al. 1996). The result is less nursing opportunity, and—because fewer maternal nutrients are allocated to milk—lower rates of milk intake. Factors that individually or collectively reduce a female's ability to raise a calf also reduce her ability to restore her body reserves, to fatten, and to breed (Crête and Huot 1993).

Tradeoffs therefore are inevitable: If maternal protein or fat reserves are not replenished fast enough, calves are weaned prematurely (Russell and White 2000). Calf survival is reduced by early weaning, but parturition and conception rates increase (Davis et al. 1991, Russell and White 2000). Delayed weaning enhances calf survival, but extended lactation precludes breeding that year (Gerhart et al. 1997a,b; Russell and White 2000). By comparison, well-fed cows initiated weaning during the rut, and both calf survival and fecundity are high.

During August and September, when insects are absent, growth of calves and fattening of adults continue relatively unimpeded. Milk production is low (White and Luick 1984), and offspring graze actively (Russell et al 1993) as they approach nutritional independence. Although most forage species have senesced, with a decline in quality, their high biomass permits high rates of food intake (White et al. 1975) and, therefore, body-fat synthesis. Fattening is enhanced in some years by the inclusion of mushrooms in the diet (Allaye-Chan et al. 1990). An unseasonably early, heavy snowfall, however, can disrupt the fattening process, and movement into more mountainous terrain increases exposure to predators. Hunting by humans tends to intensify in early autumn as well.

Females that wean their calves early, together with most that are in good enough condition to wean at normal times, conceive in October (Russell and White 2000). Cows in superior condition are less likely to lose their embryos early (Crête and Huot 1993, Russell et al. 1998), and, hence, are more likely to produce a calf the next spring.

A dietary shift from deciduous vegetation to lichens, begun in autumn, is virtually complete by midwinter. Males and nonpregnant females typically maintain body weight (Steen 1968) even when weather and foraging conditions are unfavorable. In contrast, pregnant females, faced with the increasing metabolic demands of a growing fetus, have difficulty maintaining nitrogen balance. They metabolize muscle tissue and conserve body fat during the last trimester to support early lactation (Chan-McLeod et al. 1994, Tyler 1987). Adequate winter nutrition increases the chances of timely parturition and early postnatal survival (Cameron et al. 1993, Eloranta and Nieminen 1986, Rognmo et al. 1983).

When snow is deep or encrusted, foraging requires more energy because caribou must dig through the snow (Fancy and White 1985a,b; Miller 1976). Far more serious is ground-fast ice. During frequent freeze-thaw cycles, typically in coastal areas during late winter or early spring, vegetation under the snow becomes encased in ice and thus inaccessible (Miller and Gunn 1979, Miller et al. 1982). As during autumn, mortality from predation and hunting can be appreciable.

Effects on Distribution, Movements, and Activity Patterns

Seismic Surveys

Until recently, the location and timing of seismic testing resulted in few conflicts with caribou in arctic Alaska. Surveys on state lands through the 1990s were conducted principally within the area of the CAH summer range, but during winter, when caribou were largely absent. Similarly, long-term programs within the National Petroleum Reserve-Alaska during the 1970s and 1980s occurred mostly within the summer ranges of the TLH and WAH, but again during winter. Seismic exploration crews on the coastal plain of the Arctic National Wildlife Refuge in the 1980s had no contact with caribou of the PCH, which winters south and east of the Brooks Range.

Even when seismic testing was conducted on winter range, the direct effects on caribou were probably temporary and minor. Early two-dimensional (2-D) surveys were of low intensity and, because wintering bands of caribou tend to be small and often widely dispersed, few caribou would have been in simultaneous contact with seismic activities. Moreover, caribou appear least sensitive to human-induced disturbance during winter (Roby 1978).

Recently, however, both the extent and intensity of seismic activities have increased. Active exploration now extends southward into the upper foothills of the central Brooks Range and westward to new lease tracts in the northeastern portion of the National Petroleum Reserve-Alaska. With a seismic line density 10-20 times greater than that for 2-D procedures, expanded application of the new three-dimensional (3-D) technology in those areas will increase the potential for conflicts with the CAH and TLH. Avoidance of seismic lines and the attendant human activity could reduce the animals' ability to avoid areas of deep snow (Dyer et al. 2001). The energy costs of multiple encounters with seismic disturbance could increase winter weight loss and reduce calf production and survival (Bradshaw et al. 1998).

Exploration and Drilling

Most exploration drilling—a site-specific, high-intensity event—is not connected to a permanent road system. As novel features on the landscape, drilling sites that are active in late spring almost certainly would be avoided by calving caribou. During midsummer, effects include localized changes in habitat use, longer approach distances, and altered activity patterns (Roby 1978, Wright and Fancy 1980). Caribou did not approach a drilling site closer than 1,200 m (0.7 mi) and were seen less frequently within 2 km (1.2 mi) of a drilling site than in a control area. Those entering the drilling area spent less time feeding and lying and more time moving than did caribou in a control area (Wright and Fancy 1980). In studies involving a simulated gas compressor station, caribou usually avoided the source of sound by at least 0.2 km (0.12 mi) (McCourt et al. 1974). Sensitivity appears to decline during other seasons, when calves are older.

Isolated Roads and Pipelines

Perhaps as an anti-predator strategy (Bergerud and Page 1987), parturient females and postpartum females with newborn calves distance themselves from potentially threatening stimuli. Aerial survey observations before and after placement of a road system (and later, an aboveground pipeline) through a calving concentration area near Milne Point (Whitten and Cameron 1985), in the Kuparuk Development Area (KDA), illustrate that sensitivity. After construction, the density of maternal females increased with distance from roads; no relationship was apparent before construction (Dau and Cameron 1986). Mean caribou abundance declined by more than two-thirds within 2 km (1.2 mi) of roads and was less than expected, overall, within 4 km (2.5 mi); but abundance nearly doubled at 4-6 km (2.5-3.7 mi) (Cameron et al. 1992), resulting in two separate concentrations (Dau and Cameron 1986, Lawhead 1988, Smith and Cameron 1992). Road traffic was light during the study (Dau and Cameron 1986; Dau and Smith, unpublished data; Lawhead 1988), suggesting that the presence of a road or pipeline alone, without vehicular or human activity, can elicit avoidance.

Concurrent ground observations within the KDA corroborate those findings. Few females and calves were seen from the road system during early June, and correspondingly few were observed crossing roads or pipelines (Smith et al. 1994). This is consistent with a tendency for parturient females to be relatively sedentary during the calving period (Fancy and Whitten 1991, Fancy et al. 1989).

A similar pattern of avoidance of a tourist resort and separate power-line corridor has been reported for semi-domesticated reindeer (*Rangifer tarandus tarandus*) during the calving period. Mean reindeer densities within preferred habitat were 73% and 78% lower in areas less than 4 km (2.5 mi) from the resort and power-line corridor, respectively, than in areas beyond 4 km (2.5 mi). Traffic and human activity were low, again implying a dominant influence of the structures themselves (Vistnes and Nellemann 2001).

From late June through July, sensitivity to disturbance appears to decline as calves mature and are less vulnerable to predation and other sources of mortality. Maternal females are less protective and therefore less reactive to novel stimuli than during the calving period. Also, when insect harassment is high, caribou are less likely to avoid anthropogenic disturbances (Murphy and Lawhead 2000).

Even so, avoidance of transportation corridors can persist through summer. During construction of the Trans-Alaska Pipeline, 1975-1978, calves were increasingly underrepresented among caribou observed from the Dalton Highway; calf percentages, on average, were 69% lower than regional estimates determined by aerial survey. Caribou sightings within, and crossings of, the pipeline corridor in 1976-1978 averaged 30% and 80% less, respectively, than did those in 1975 (Cameron and Whitten 1980, Cameron et al. 1979). Collared males crossed the corridor more frequently than did collared females (Whitten and Cameron 1983). Jakimchuk and colleagues (1987) attributed those observations to sex differences in habitat use, arguing that maternal females avoid riparian habitats to reduce the risk of predation by grizzly bears along the Sagavanirktok River, which is adjacent to the pipeline corridor. A reexamination of the data, however, revealed that bull numbers were high and calf numbers were low only within riparian areas associated with the corridor (Whitten and Cameron 1986). Young and McCabe (1998) reported neither avoidance of riparian habitats by PCH females nor selection of those habitats by bears; they also rejected the antipredator explanation.

Similar avoidance was observed within the KDA, during placement of the smaller Kuparuk pipeline along the Spine Road and during construction of the first processing facility. Calves were underrepresented in groups observed in areas of heavy construction and traffic (Smith et al. 1994).

Within the CAH summer range, crossing success[2] varies with design and juxtaposition of roads and pipelines, as well as with the amount of vehicular traffic. Most early pipelines in the Prudhoe Bay oil-field complex (PBOC) were constructed 1 m or less above ground, posing physical barriers to movement (Shideler 1986). Gravel ramps were placed over some low pipelines to encourage crossings, but anecdotal observations indicated that caribou made limited use of those structures. In the adjacent KDA, however, all pipelines were elevated at least 1.5 m (5 ft), and ramps were built at road intersections. Curatolo and Murphy (1986) reported no selection for particular surface-to-pipe clearances within the range of 1.5-4.3 m (5-14.1 ft), indicating that, under most conditions, the regulatory standard of 1.5 m (5 ft) is sufficient for caribou crossings (Cronin et al. 1994, Curatolo and Murphy 1986). However, crossing success at elevated pipelines close to roads with traffic was lower than for pipelines without associated roads and traffic (Curatolo and Murphy 1986). Large mosquito-harassed groups had particular difficulty negotiating road-pipeline corridors (Child 1974; Curatolo and Murphy 1986; Fancy 1983; Smith and Cameron 1985a,b). Crossing success appears to increase during the oestrid fly season, but it is unclear whether that is attributable to the presence of smaller groups or to different reactions to the two insect pests (Smith and Cameron 1985a). Under some circumstances, ramps enhance pipeline crossings (Child 1973, Cronin et al. 1994, Curatolo and Murphy 1986, Shideler 1986, Smith and Cameron 1985b).

Effects on caribou activity near road-pipeline corridors are most pronounced when there is no insect harassment. During insect-free periods, maternal and nonmaternal groups within 600 m (2,000 ft) of a corridor with traffic spent less time lying and more time moving than did controls. Maternal groups and groups of more than 10 individuals were most reactive to disturbance (Murphy 1988, Murphy and Curatolo 1987).

---

[2] Curatolo and Murphy (1986) considered a crossing successful when more than half of an observed group crossed a road and/or pipeline (or a hypothetical pipeline in a control site). Success was then expressed as a percentage which was evaluated statistically by comparison with the corresponding "expected" percentage obtained from the control site.

From autumn through early spring, the CAH has considerably less contact with industrial development. By the autumn rut, most of the herd has moved well inland (Cameron and Whitten 1979a). Only those few caribou that winter on the coastal plain are likely to interact with oil fields, and the effects appear to be minor. However, females with calves avoided inland portions of the Trans-Alaska Pipeline corridor during its construction. Calf percentage for caribou near the Dalton Highway was approximately representative of regional percentages in 1975, but diverged during 1976-1978, averaging 32% less than regional estimates. Sighting frequency declined about 60%, relative to the 1975 estimate, but crossing rates were inconsistent (Cameron and Whitten 1980, Cameron et al. 1979). Overall, avoidance of the pipeline corridor by females with calves decreased measurably between summer and autumn, correlated with the advanced age of the calves and distractions of the rut. Habituation to construction activity is also a possibility.

Oil-Field Complexes

Given that calving caribou avoid roads and pipelines (Cameron et al. 1992, Dau and Cameron 1986), their densities should be reduced in areas with corridors closer together than some minimum distance. In fact, the proportion of calving caribou in the densely developed western portion of the KDA declined significantly from 1979 through 1987 (Cameron et al. 1992). Concentrated calving activity shifted inland from the Milne Point area beginning about 1987 (Lawhead et al. 1993, 2002; Murphy and Lawhead 2000; Wolfe 2000), associated with the increasing density of oil-field infrastructure. Caribou did not abandon the area near Milne Point (Lawhead et al. 2002, Nellemann and Cameron 1996), but continued to occupy the KDA in numbers consistent with the amount of undisturbed habitat. Other explanations advanced for the inland shift west of the Sagavanirktok River include expansion of the calving ground with increasing herd size, changing vegetation characteristics, and parasite avoidance (Lawhead et al. 2002). One or more of these factors could have accelerated that process. However, none explains the absence of a similar shift by the undisturbed part of the caribou herd east of the Sagavanirktok River (Wolfe 2000).

During the summer insect season, dense surface development within the PBOC also altered the distribution of caribou, especially females with calves. As early as 1978, mean calf percentage in the core area of the industrial complex was less than half the minimum regional estimate (Smith and Cameron 1983). With continued growth of the complex, changes in caribou distribution became even more pronounced. An analysis of more than 1,200 point locations of 141 radio-collared females (Cameron et al. 1995) suggests that caribou use of the area has declined substantially from that noted by Child (1973), White and colleagues (1975), and Gavin (1978). From 1980 through 1993, abundance within and east-west movements through the area were lower than for other areas along the arctic coast. Conservative calculations yielded an estimated 78% decrease in use and a 90% decrease in lateral movements.

Other researchers (Cronin et al. 1998, Pollard et al. 1996a) concluded that the PBOC infrastructure has had little effect on the midsummer distribution of caribou. However, the studies lack important data needed to support that conclusion. Without spatial controls—undeveloped areas—they lacked the ability to compare the distribution of cows with calves in the field as a whole with that in either the denser central area or in the less-developed areas to the northwest. Many caribou, including some females and calves, do periodically use the

PBOC, particularly the less-developed northwestern areas (Murphy and Lawhead 2000, Ballard et al. 2000). Moreover, data reported by Pollard and colleagues (1996a) indicate that caribou were numerous in the PBOC only during periods of moderate or high insect harassment and that females with calves generally were underrepresented. These latter data and evidence for reduced abundance and movements of females with the complex (Smith and Cameron 1983, Cameron et al. 1995) indicate that patterns of caribou use have been appreciably altered.

Changes in Habitat Use

Ecological theory and data support the premise that animals generally select the best available areas for reproductive activity. For calving CAH caribou, the probable consequence of disturbance-induced changes in distribution is selection of lower-quality habitats. The number of caribou affected is directly related to the area and intensity of disturbance, which could range from the localized avoidance of an isolated road to a regional shift of large calving concentrations away from areas occupied by multiple oil field complexes. With the gradual loss of access to preferred foraging habitats, increasingly more females seek "next best" available areas. As those areas become insufficient to accommodate the population, use declines at a rate proportional to the increase in density of structures (Nellemann and Cameron 1998, UNEP 2001).

The shift in calving activity west of the Sagavanirktok River might have increased predation risk, particularly in recent years. Since at least 1995, the inland calving concentration west of the river has overlapped extensively with relatively high densities of brown bears (R. Shideler, unpublished data). However, estimates of calf survival during 1988-2001 were similar west and east of the river (84% and 88%, respectively; $P = 0.426$) (Table 8-1), implying that any increase in mortality attributable to predation was compensatory (that is, predation on calves predisposed to die from other causes).

Oil-field infrastructure also can delay or prevent access to insect-relief areas and foraging habitats. In the KDA, the lower success of or delays in crossing road-pipeline corridors by large insect-harassed groups of caribou (Curatolo and Murphy 1986, Murphy 1988, Murphy and Curatolo 1987, Smith and Cameron 1985b) apparently encouraged a general shift to peripheral areas of the complex with less surface development and human activity. Routes of movement within and through the KDA are now primarily in the Oliktok Point/CPF-3 area and along the Kuparuk floodplain (Smith et al. 1994). This shift suggests that caribou were impeded in their efforts to move between coastal and inland habitats.

Much of the PBOC poses a behavioral, if not a physical, barrier to movement of adult females at times (Cameron et al. 1995, Whitten and Cameron 1983). Radio-collared females were scarce in the most densely built (and oldest) part of the complex (Figures 8-4 and 8-5), especially when insects were relatively inactive. During periods of moderate to high insect activity, caribou south of the complex often divert eastward, into the prevailing northeasterly winds, to the Sagavanirktok River and move downstream to the coast (Lawhead et al. 1993). Alternatively, caribou might occupy gravel pads for insect relief (Noel et al. 1998, Pollard et al. 1996b, Truett et al. 1994) when other habitats are unavailable (Wolfe 2000).

Table 8-1 Parturition rates of radiocollared female caribou[a] and summer survival of their calves, west and east of the Sagavanirktok River[b], during 1988-1994[c] and 1998-2001[d]. Central Arctic Herd, Alaska.

	Parturition rate, %[e] (*n*)			Calf survival, %[f] (*n*)		
Years(s)	West	East	*P*[g]	West	East	*P*[g]
1988	72.7 (11)	100.0 (8)		66.7 (6)	100.0 (6)	
1989	53.8 (13)	77.8 (9)		83.3 (6)	60.0 (5)	
1990	83.3 (12)	100.0 (7)		85.7 (7)	60.0 (5)	
1991	45.5 (11)	75.0 (12)				
1992	72.7 (11)	75.0 (12)		87.5 (8)	100.0 (9)	
1993	55.6 (9)	62.5 (8)		100.0 (5)	100.0 (5)	
1994	66.7 (6)	87.5 (8)		75.0 (4)	85.7 (7)	
1988-1994	64.3 ± 5.0	82.5 ± 5.3	0.003	83.0 ± 4.6	84.3 ± 8.0	0.898
1998	92.3 (13)	100.0 (6)		90.9 (11)	100.0 (6)	
1999	100.0 (13)	100.0 (8)		88.8 (9)	100.0 (8)	
2000	83.3 (12)	90.0 (10)		77.8 (9)	77.8 (9)	
2001	90.9 (11)	100.0 (7)		80.0 (10)	100.0 (5)	
1998-2001	91.6 ± 3.4	97.5 ± 2.5	0.062	84.4 ± 3.2	94.4 ± 5.5	0.091
All years	74.3 ± 5.3	88.0 ± 4.1	0.001	83.6 ± 2.9	88.4 ± 5.3	0.426

[a] All sexually-mature.
[b] Individual locations consistently west (oil field development present) or east (no surface development, except for the Badami pipeline and oil field beginning in 1996) during the calving period.
[c] Forty-three females observed for 2-7 years (Cameron 1995; Cameron et al. 2002).
[d] Twenty-nine females observed for 2-4 years (Lenart, ADF&G, unpublished data, 2002).
[e] Based on parturition status determined by fixed-wing aircraft (Cameron et al. 1993).
[f] Percentage of parturient females with calf at heel 2-6 weeks postpartum.
[g] *t*-test, paired comparisons. Mean and standard errors shown.

Changes in distribution and movements during calving and when insects are present reduce the capacity of the range to support CAH caribou. This is due to loss of preferred habitats (Cameron et al. 1995, Wolfe 2000) and through correspondingly greater use of lower-quality habitats (Klein 1973, Nellemann and Cameron 1996, Wolfe 2000).

Nutrition and Reproductive Implications

The reproductive success of arctic female caribou is highly correlated with their nutritional status. Parturition rate varies directly with body weight or fat content during the previous autumn (Cameron and Ver Hoef 1994; Cameron et al. 1993, 2000; Gerhart et al. 1997a), whereas calving date and survival within about 48 h after birth are more closely related to maternal weight at the time of parturition (Cameron et al. 1993).

Those relationships form the link between the disturbance-induced changes in distribution described above and potential changes in reproductive success. Wolfe (2000) studied 96 radiocollared females at 183 calving sites from 1980-1995. Concentrated calving areas west of the Sagavanirktok River (closer to areas of petroleum activity) shifted inland away

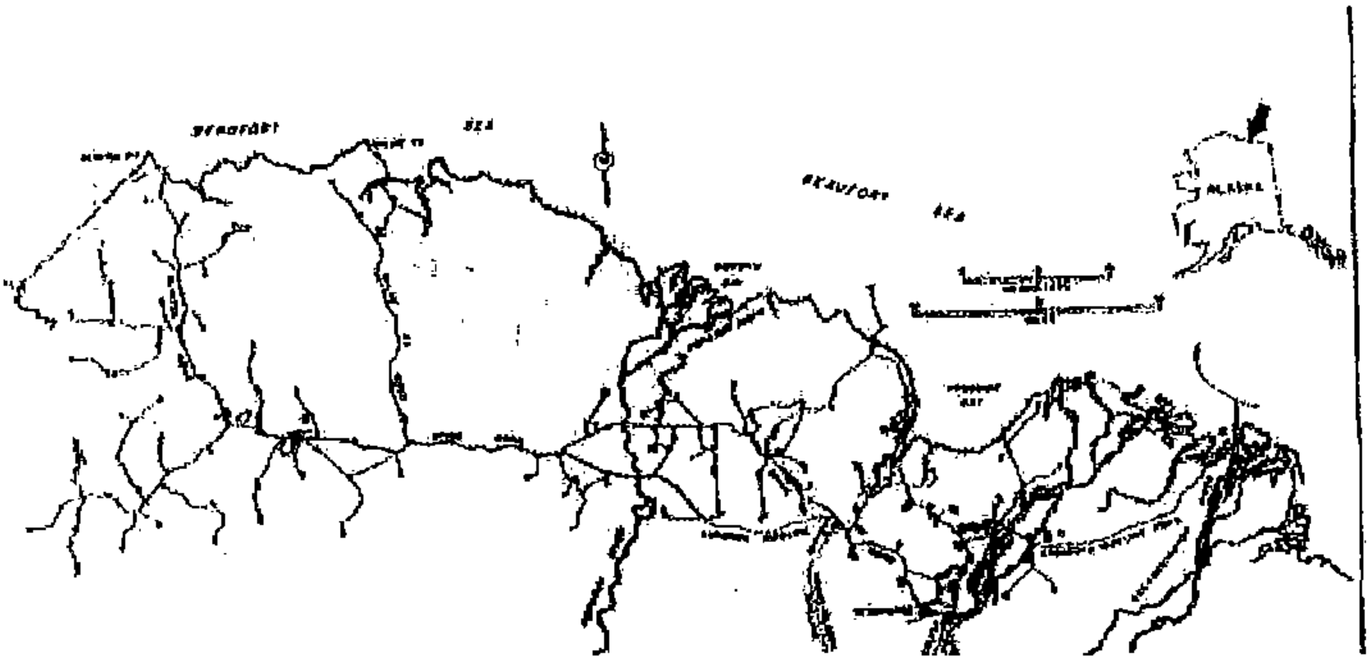


FIGURE 8-4. Roads and pipelines in the Prudhoe Bay region, Alaska, ca. 1990. Note: One or more pipelines (stippled) are adjacent to most roads. Source: Cameron et al. 1995.

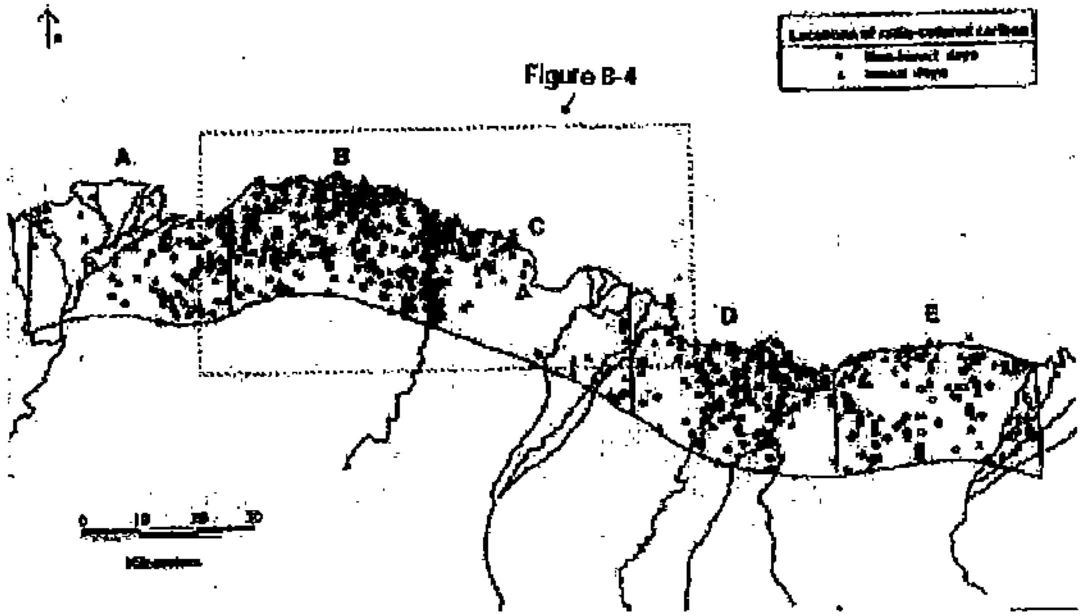


FIGURE 8-5. Locations of radiocollared female caribou within 850-km² coastal quadrants in relation to insect activity. Central Arctic Herd, Alaska, summer 1980-1993. Note: Some points represent >1 female in a single group. Source: Cameron et al. 1995.

from development into habitats with lower green-plant biomass.[3] On the east side of the river, an area without development, no such shift in calving was observed: Females selected habitats with above-average green-plant biomass (Wolfe 2000). For the PCH, calf survival through their first few weeks is primarily a function of the relative amount of forage available on the annual calving ground during the peak lactation period (Griffith et al. 2000a, 2002). However, survival estimates (Table 8-1) and Wolfe's (2000) NDVI data do not suggest such a relationship for the CAH, but sample sizes are small.

Impaired movements during the insect season also could decrease energy balance (Murphy and Lawhead 2000, Russell 1976, Russell et al. 1993, Smith 1996, Weladji et al. 2002, White et al. 1975) and hence reduce rates of summer weight gain. However, changed activity patterns of caribou near transportation corridors (Murphy 1988, Murphy and Curatolo 1987) might not reduce weight gain enough to depress parturition rates (Murphy et al. 2000). Nevertheless, individual or collective conflicts that result in nutrient insufficiency can decrease fecundity.

In fact, from 1988-1994, the mean parturition rate for radio-collared females west of the Sagavanirktok River was 64%, compared with 83% for those east of the river ($P = 0.003$). Parturition rates were similar from 1998 through 2001 (92% and 98%, respectively; $P = 0.062$), but differed for the eleven years overall (74% and 88%, respectively; $P = 0.001$) (Table 8-1). Estimated frequencies of reproductive pauses (periodic failure to produce a calf because of poor condition at breeding) (Cameron 1994, Cameron and Ver Hoef 1994) for the combined data were 26% and 12%, or approximately one pause every 4 and 8 years, respectively.

This longitudinal analysis provides a reliable assessment of difference in reproductive success. Because radio-collared females were used, interannual shifts of individual females between areas west and east of the Sagavanirktok River (Cronin et al. 2000; Lawhead and Curatolo 1984, cited in Murphy and Lawhead 2000; Whitten and Cameron 1984) could be detected and samples adjusted accordingly, yielding multiyear histories of females that had consistent use of the two areas.

Lower fecundity of females west of the river could be due to inadequate compensation for milk production (Cameron and White 1992). By reducing rates of forage intake or increasing rates of energy expenditure, conflicts during the calving and insect periods might diminish chances of achieving the weight gain required to support annual reproduction (Cameron and White 1992, Russell et al. 2000). In general agreement are anecdotal reports from Nuiqsut residents that caribou taken recently have been leaner than in years past (Miller 2001, Pedersen et al. in press).

Population Dynamics

Observed changes in the size of the CAH (Figure 8-6) are correlated with estimates of net calf production—the product of parturition rate and calf survival. From 1978 through 1983, when the herd increased, on average, 16% annually, net calf production exceeded 90%. The next census was not done until 1992, so the trajectory in herd size during the intervening period is not known; but the steady decrease in net calf production implies a deceleration of growth though the early 1990s. Between 1992 and 1995, years with consistently low productivity, the

[3] The actual measurement was a Normalized Difference Vegetation Index (NDVI), which measures the amount of land-cover greenness. The NDVI value can vary with species composition and other factors (Jia et al. 2002).

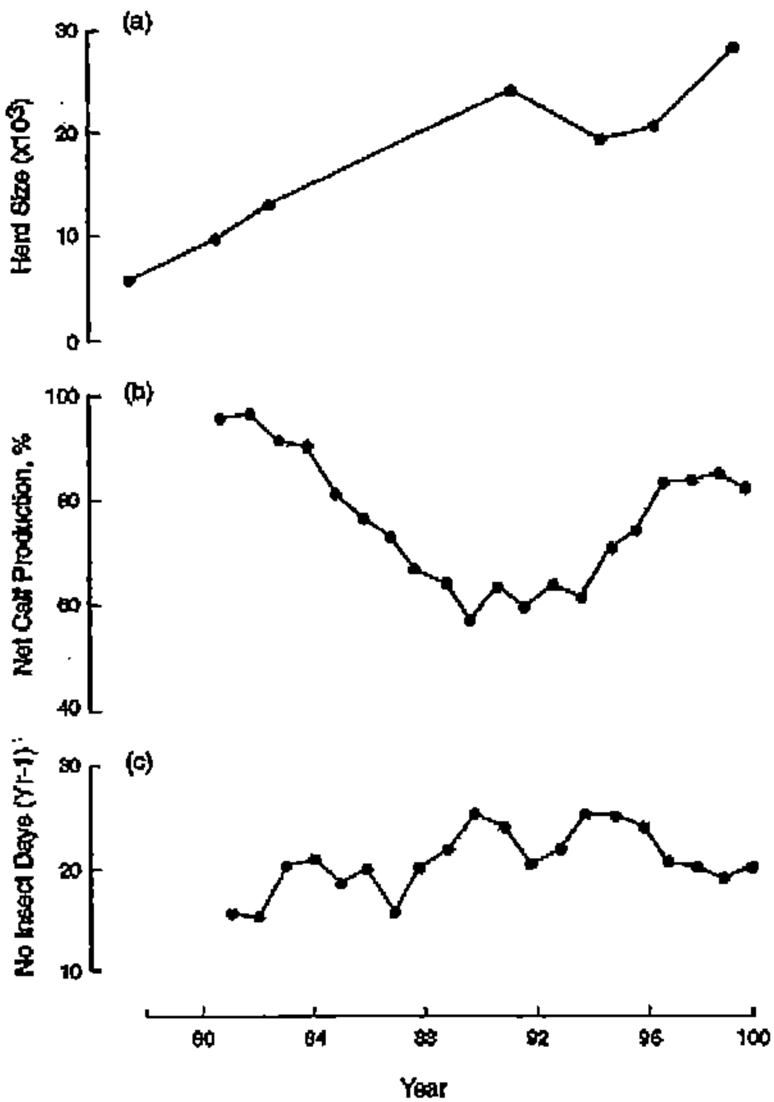


FIGURE 8-6. Central Arctic Herd in Alaska. (a) Herd size, 1978-2000. Point estimates determined by photo-census. (b) Net calf production. Three-year moving averages of radio-collared female caribou, 1981-2000, Lenart 2001, ADF&G files. Percentage of parturient females with a calf at heel ca. 2-8 weeks postpartum; approximate equivalent of the product of parturition rate and over-summer calf survival (see Table 8-1). (c) Number of insect days in July. Three-year moving averages, 1980-1999. Weather data for Deadhorse Airport, Alaska State Climate Center, UAA applied to the predictive models of Russell et al. 1993; criteria for insect days from Cameron et al. 1995.

CAH actually declined by about 8% per year. From 1995 until the census in 2000, the herd increased 14–15% annually, correlated with a sustained increase in net calf production.

Net calf production is affected by factors that influence acquisition and retention of nutrients. An important factor is insect activity. From 1981 through 2000, net calf production was inversely correlated with the number of days of high insect activity in July of the previous year (Figure 8-7) (Spearman's rank, $P = 0.012$). A lower frequency of insect-induced movements and insect avoidance behavior enable caribou to spend more time in high-quality habitats, thereby increasing chances that they will eat enough to produce milk. Maternal females would then experience greater weight gain, superior condition at breeding, and a higher probability of producing a calf the following spring.

Because parturition rate accounts for most of the variability in net calf production (Table 8-1), the committee focused on differences in parturition rate that might be related to level of insect activity. Dividing the 11 paired estimates of parturition rate west and east of the Sagavanirktok River into (previous) years of low and high insect activity yielded significant differences within each category ($P = 0.043$ and $P = 0.004$, respectively; Figure 8-7). When insects were relatively inactive, mean parturition rate of females west of the River was only about 10% lower than for those to the east. Following years of relatively high insect activity, however, the reduction was more than 25%.

Thus, oil-field development, by delaying or deflecting movements of caribou within and between habitats (Murphy and Lawhead 2000, Smith and Cameron 1985, Smith 1994), probably exacerbates the adverse effects of insect harassment. If the ability to forage or escape insects is sufficiently reduced, nutrition and fecundity will decline, with direct consequences for herd growth. Indeed, decreasing herd size in 1992 to 1995 (Figure 8-6) was associated with relatively high insect activity (2 of 3 years, 1992-1994). The subsequent trend of increasing size from 1996 through 2000 occurred during a period of generally low insect activity (3 of 5 years, 1995-1999).

Net growth of the CAH over the past 25 years is not, by itself, sufficient evidence for the absence of any adverse effect of petroleum development on caribou (WMI 1991). We cannot know what the growth trajectory of the herd would have been in the absence of oil-field development. However, multiyear data on the reproductive performance of collared CAH females exposed to oil-field development, relative to an undisturbed control group, indicate that productivity did decline when the attendant disturbance and habitat losses were superimposed on other conditions that adversely affected nutrient balance. Interestingly, these changes occurred during a period in which the growth rate of the CAH decreased relative to that of the similar TLH (Figure 8-3).

Future Effects

The results of the committee's analysis of the consequences of petroleum-related disturbance to CAH caribou provide a basis for assessing the probable future effects on the CAH and other arctic herds of the likely expansion of oil and gas development over the next 25 years eastward on state lands from the Badami unit, southward into the foothills of the central Brooks Range, and westward into the National Petroleum Reserve-Alaska from the Alpine unit. Unless the density of new access roads and new production and support facilities can be substantially reduced relative to infrastructure now in place, conflicts with CAH caribou east of the

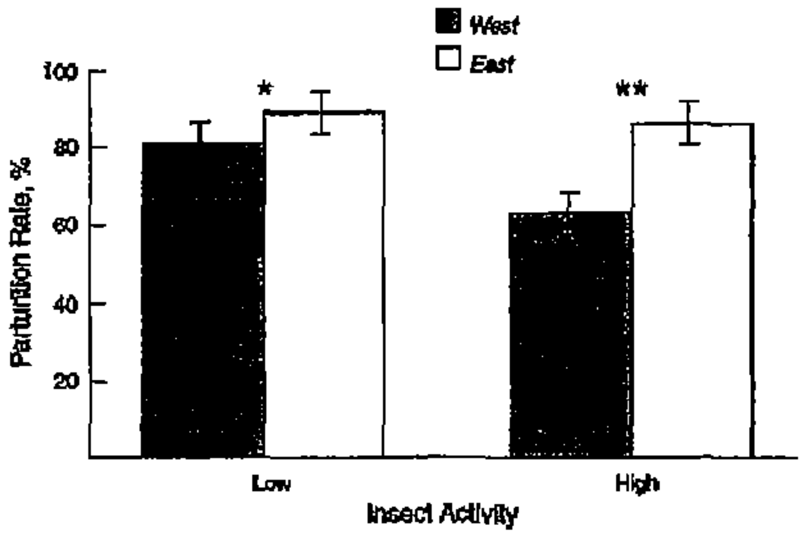


FIGURE 8-7. Parturition rates of 72 radio-collared female caribou of the Central Arctic Herd in Alaska west and east of the Sagavanirktok River, 1988-2001, following years of low and high insect activity. Determined, respectively, as the number of insect days below and above the median of 20.5 days (range, 15-27) for 1987-2000 (see Fig. 8-5 legend). *$P = 0.043$, paired t-test. **$P = 0.004$, paired t-test.

Sagavanirktok River will increase during the calving and insect-harassment periods. Higher insect activity associated with climate warming could counteract benefits of reduced surface development by increasing the frequency with which caribou encounter infrastructure (Klein 1999). With inland expansion, more of the CAH will come into contact with development on this winter range, with unknown consequences. If the calving ground of the TLH continues to be protected, direct conflicts with parturient females of that herd are unlikely, provided that their movements are not impeded. However if inland lease tracts in the northeastern portion of the National Petroleum Reserve-Alaska are developed, effects on midsummer distribution, habitat use, and productivity of TLH caribou are possible. The exact outcome and the degree to which these effects would accumulate depend on a host of unknowns, including characteristics of the oil and gas reservoir and advances in extraction technology. Within the next 25 years, major expansion of industrial activity into the WAH calving ground is unlikely, and inroads to its primary summer range are expected to be modest. If so, effects should be minor and not accumulate significantly.

If a proposed road north of the Red Dog mine to a North Slope site of a coal-fired power plant were constructed, it would cross a major east-west zone of travel, possibly interfering with insect-induced movements. A road would also open the region to further development.

To date, oil and gas activities have had little influence on the Porcupine Herd, but petroleum exploration and subsequent development on the coastal plain (1002 Area) of the Arctic National Wildlife Refuge could lead to development on the calving ground of that herd. To assess the potential effects of such developments on the PCH, Griffith and colleagues (2002) combined pertinent information on the CAH with the extensive data on the PCH. They simulated the effects of progressive development of the 1002 Area by displacing 17 annual calving grounds, between 1985 and 2001, using five scenarios (Clough et al. 1987). The concentrated calving area within each annual calving ground was repositioned 4 km (2.5 mi) from the periphery of industrial infrastructure. June calf survival was then calculated for each annual calving ground observed and for those hypothetically displaced, using a predictive model based on forage biomass during peak lactation and predation risk. A significant ($P < 0.0001$) inverse relationship was obtained between change in calf survival and displacement distance, even though calving still remained primarily on the coastal plain where habitat was good for foraging and predator avoidance. The results of these simulations suggest that an average displacement of approximately 27 km (17 mi) would be sufficient to halt growth of the PCH.

Consequences similar to those reported for the CAH are possible on PCH summer range, depending upon the extent and intensity of surface development. Impaired movements during years of high insect activity could reduce weight gain of lactating females, with comparable effects on fecundity (Figure 8-7). If superimposed on reduced calf survival (Griffith et al. 2002), the additive effects on PCH productivity could be substantial.

The PCH has the lowest growth capacity of the four arctic herds and, consequently, the least capacity to resist natural and anthropogenic stresses (Griffith et al. 2002). That vulnerability is, in part, attributable to the critical importance during calving of free access to the highest quality foraging and predator-avoidance habitats and to a lack of suitable alternative habitats (Griffith et al. 2002).

It is impossible to characterize future development infrastructure and activity in areas that have not been fully explored. Until exploration has occurred, the amount, distribution, and exact nature of any extractable hydrocarbon deposits remain unknown. But the amount, distribution, and type of hydrocarbon deposits profoundly influence the nature and extent of development infrastructure, thus how many roads and pipelines will be needed, and how much activity will occur and when it will occur. Current technology will probably continue to evolve, as discussed elsewhere in this report, but adverse effects on caribou are likely to increase with both the density of infrastructure development and the area over which it is spread.

Findings

- The intensively developed part of the PBOC has altered the distribution of female caribou during the summer insect season. Elsewhere, a network of roads, pipelines, and facilities has interfered with their movements between coastal insect-relief and inland feeding areas. Possible consequences of these disturbances include reduced nutrient acquisition and retention throughout the calving and midsummer periods, poorer condition in autumn, and a lowered probability of producing a calf in the following spring.
- Pregnancy rates and survival of young caribou during their first summer is positively correlated with the availability of food. Insect harassment reduced nutrient-intake rates by females of the CAH as the animals moved to habitats where they could avoid insects but where they foraged less efficiently. Radio-collared female caribou west of the Sagavanirktok River shifted their main calving area from developed areas nearer the coast to undeveloped areas inland. No such shift has occurred for caribou calving east of the Sagavanirktok River where there is no development. The shift by caribou west of the Sagavanirktok River was into an area with lower green-plant biomass than the area previously used. From 1988 to 1994, parturition rates of radio-collared females in regular contact with oil-field infrastructure west of the Sagavanirktok River were lower than those of undisturbed females to the east. Reduction in parturition rates—the variable part of net calf production—for those caribou was exacerbated by intense insect harassment during the period. Thus, it appears that the effects of oil-field development accumulate with effects of insect harassment by impairing movements between coastal and inland habitats.
- As a result of conflicts with industrial activity during calving and an interaction of disturbance with the stress of summer insect harassment, reproductive success of Central Arctic Herd female caribou in contact with oil development from 1988 through 2001 was lower than for undisturbed females, contributing to an overall reduction in herd productivity. The decrease in herd size between 1992 and 1995 may reflect the additive effects of surface development and relatively high insect activity, in contrast to an increase in the herd's size from 1995 through 2000, when insect activity was generally low.
- For the females of the CAH west of the Sagavanirktok River, avoidance of expanding infrastructure in the region triggered changes in distribution, progressing from localized adjustments to major shifts in the use of calving and summer habitats. Expanded loss of preferred habitats, which could accompany the spread of industrial activity across the National Petroleum Reserve-Alaska and into the foothills of the Brooks Range, and climate change that increases insect harassment, are likely to depress nutrient status and, therefore, summer weight gain of lactating females.
- Unless future requirements for infrastructure can be greatly reduced, exploitation of oil and gas reserves within the calving and summer ranges of the CAH, TLH, and PCH will likely have similar consequences.

Recommendations

- Determine the responses of caribou to seismic testing under different snow conditions and estimate the probable consequences in terms of energy intake and nutrient balance and reproductive success.
- Determine the minimum distance between road-pipeline corridors that is compatible with continued use of an area by calving caribou and how design of corridors influences those effective distances.
- Studies are needed to characterize the nutrient-energy tradeoffs associated with insect-induced movements; quantify the conditions of nutrient intake and body condition associated with each of the various weaning decisions (tradeoffs) made by maternal females; and within known levels of exposure to disturbance, determine the over-summer nutritional performance of females and their calves.
- Determine whether winter calf mortality is additive or compensatory, relative to early postnatal mortality; that is, do those that survive unfavorable foraging conditions in spring or summer die during the winter anyhow?

MUSKOXEN

Muskoxen (*Ovibos moschatus*), which were exterminated from Alaska, have been reintroduced and are now found at low densities on the North Slope, mostly in riparian areas. Populations are expanding into other habitats. Helicopters and low-flying aircraft sometimes cause muskoxen to stampede and abandon their calves (Winters and Shideler 1990). Seismic exploration is of concern because muskoxen are present year-round on the North Slope. The response to the noise of seismic exploration appears to differ from herd to herd, perhaps because of each herd's previous experience. Some seem unaffected by seismic activities as close as 300 m (980 ft); others appear disturbed by activity 10 times more distant (Winters and Shideler 1990). Therefore, although no adverse effects have been recorded to date, the expansion of 3-D seismic exploration to primarily unsurveyed areas, particularly in riparian areas, could result in increased disturbance to this species.

Finding

No effects of seismic exploration on muskoxen have been detected to date. However, the expansion of 3-D seismic exploration to new areas, particularly in riparian areas, might increase disturbance to this species.

ARCTIC FOXES

Past and current industrial activities on the North Slope have probably increased the availability of shelter and food for the arctic fox (*Alopex lagopus*). Developed sites within the Prudhoe Bay oil field are used by foxes for foraging on garbage and handouts, and for resting.

Foxes do not avoid human activity—successful litters of pups have been raised within 25 m (80 ft) of heavily traveled roads and within 50 m (160 ft) of operating drill rigs. Foxes use culverts under roads, underground utility corridors in camps, and sections of natural gas pipe as dens (Eberhardt et al. 1982).

In Prudhoe Bay, foxes use developed sites more in winter, when food is more likely to be scarce, than in summer. In December radiotagged foxes spent much of their time on and around developed sites, with large concentrations near dumps and other developed areas (Eberhardt et al. 1983a). During summer, garbage was commonly found at den sites near Prudhoe Bay (Garrott et al. 1983).

The density and rate of occupancy of dens and the sizes of litters, are greater in oil fields than in adjacent areas, so the fox population has grown larger and more stable (Burgess 2000, Eberhardt et al. 1982, 1983b). To reduce the possibility of transmission of diseases, especially rabies, to humans, oil companies have developed employee education programs and have trapped and removed foxes (Burgess 2000). With careful employee education and proper refuse-handling procedures, problems with arctic foxes can be reduced.

Another issue of concern is the foxes' potential to affect populations of nesting birds. Birds are a normal prey (Garrott et al. 1983), and migratory species can provide an especially important food source (Stickney 1991).

Future Effects

In the scenario the committee has used for future development, oil and gas exploration and production would occur on the entire Arctic Coastal Plain outside of the Arctic National Wildlife Refuge. The arctic fox population is likely to increase throughout that region. The current concerns about foxes would then be applied to a more expanded area. A long-term higher density of foxes could result in reduced nesting success and smaller regional populations of some species of birds (Burgess 2000).

Effects of predation can be locally devastating to colonial birds that nest in areas normally inaccessible to foxes (Quinlan and Lehnhausen 1982). Human modifications to habitats such as roads or causeways that connect barrier islands to the mainland could cause serious problems in such circumstances. Such effects would accumulate as more area is developed and as a larger portion of a bird population's nesting habitat is affected by increased fox predation.

Other factors would interact cumulatively with industrial development to influence arctic fox populations on the North Slope over the next 25 years. In particular, habitat characteristics and abundances of prey, competitors, predators, and disease agents could change greatly with climate warming. Although it is likely that there will be more arctic foxes in developed areas in the immediate future, it is not possible to predict long-term patterns of their abundance.

Finding

The increased fox populations due to oil and gas activities could affect regional populations of some bird species.

GRIZZLY BEARS

The infrastructure that supports industrial development in the Arctic substantially increases bear-human interactions. These interactions might have created a population sink associated with industrial infrastructure that could lead to long-term effects on grizzly bear populations on the North Slope.

Development in the central Arctic increased potential hunter access by road and airstrip (Shideler and Hechtel 2000). Defense of life and property (DLP) mortality of grizzlies arises with increases in human residence and anthropogenic food availability. Shideler and Hechtel (2000) found that 21% of oil-field grizzlies supplemented natural forage with anthropogenic foods. When access to garbage and human food was suddenly eliminated, food-conditioned bears suffered DLP mortalities greater than sustainable rates (Shideler and Hechtel 2000; Shideler, personal communication 2002).

Studies of the grizzly bear populations that use Prudhoe Bay oil fields showed that bears that consumed human food resources had higher than average cub survival (possibly because of a scarcity of natural predators such as wolves, wolverines, and adult male bears). This increased cub survival was offset by greater-than-average mortality among post-weaned subadults because their conditioning to human foods made them more vulnerable to hunters along the Dalton Highway and DLP killings (Shideler and Hechtel 2000).

Bears are often drawn into human camps by simple curiosity or cooking odors; however, once there they often remain because of deliberate feeding—which is now relatively unusual—or by improperly stored food and garbage, which can lead to additional grizzly bear mortalities. Although efforts have been made to reduce food available to bears, they have been only partly successful because some individuals have become expert at defeating them. In the Prudhoe Bay oil fields, the mortality rates of all adults and subadults that fed on anthropogenic foods was significantly higher than for bears that fed on natural foods (Shideler and Hechtel 2000). Of 12 offspring weaned by 4 food-conditioned females, 7 were killed, the status of 2 was unknown, and only 3 are known to have survived (Shideler and Hechtel 2000). During the summer of 2001, 5 food-conditioned bears were killed in the Prudhoe Bay oil fields (Shideler, personal communication 2002). These DLP kills are an example of the risks facing grizzly bears following industrial development in wilderness habitat. Of 9 known grizzly bear deaths associated with oil-field development, all were within the support service enclaves outside the immediate control of the oil companies (Shideler, personal communication 2002). On the basis of this experience, support areas appear likely to be a source of human-bear interactions.

Western arctic grizzly populations are low, and they are vulnerable to increasing harvest rates. Northern and northwestern areas of the western Arctic are marginal grizzly bear habitat (Shideler, personal communication 2002), but grizzlies can be lured out of the foothills to food sources on coastal plain habitats (Johnson et al. 1992). Seismic exploration, particularly new three-dimensional techniques, could disrupt denning (Shideler, personal communication 2002).

Future Effects

Expanded oil and gas exploration and production on the North Slope does not appear likely to have a large effect on bear populations, especially if the attention to the issue of bears and garbage continues. If some bears continue to be food-conditioned, some of them probably will be killed when their food source is removed. Also, bear predation on other species such as caribou could increase (Shideler and Hechtel 2000).

Even with the best possible mitigation programs, there will always be interactions with humans who live and work in grizzly bear habitat, and some bears will be killed in defense of life and property or by accident. Also, increased access opportunities (roads and airstrips) and changes in village lifestyles or economies could result in more bears being killed for sport or subsistence.

Construction of industrial facilities results in alteration or destruction of grizzly bear habitat, and as the amount of developed area expands so will the effect on bear habitat. Issues of potential concern are the effects of disturbance from roads and from seismic exploration on denning habitat and on bears in dens and habitat alterations that influence food availability (R. Shideler, personal communication). Those effects will be greater when development expands into the foothills because grizzly bear densities are higher there than on the coastal plain (Carroll 1995, Stephenson 1995).

It is also very likely that in the next 25 years the nature of habitats available to grizzly bears on the North Slope will be affected by climate warming. How the effects on grizzly bears of development-related killing of bears, hunting, alterations of habitat, and climate warming will accumulate cannot be predicted.

Finding

Oil and gas activities on Alaska's North Slope have changed the demographics of the grizzly bear population primarily because of the availability of anthropogenic food sources.

BIRDS

To assess the accumulation of effects of oil and gas activities on birds it is necessary to understand factors that limit avian populations in areas influenced by the petroleum industry. This task is complicated because migratory species can be affected by factors away from the oil fields. The limiting factors generally involve habitat, but there are associated variables, such as the availability of food in wintering and migration areas and of the food birds need for maintenance and production of eggs or tissue on the breeding area. Hunting, primarily of waterfowl, also is of concern, as is predation on eggs, young, and adults. Habitat change in wintering or migration areas can reduce populations that breed in oil development areas independent of local effects, or can keep breeding populations below local carrying capacity. Reduced winter habitat could hamper first-year or adult survival or reduce the proportion of breeding adults by altering their ability to store nutrients required for migration and reproduction (Ankney 1982, Ens et al. 1990). Also, large molting concentrations of pintails (*Anas acuta*), long-tailed ducks (*Clangula hyemalis*), king eiders (*Somateria spectabilis*), and black Brant (*Branta bernicla nigricans*)use Alaska's North Slope and adjacent lagoons for postbreeding molting and migration. Declines in breeding populations away from the North Slope could cause declines in northern Alaska independent of local industrial activities. Such cross-seasonal effects are difficult to measure and will be considered only in the context of evaluating local effects in developed areas on Alaska's North Slope.

Dynamics of Habitat

Habitat for breeding and molting birds has been directly affected by placement of gravel fill (Gilders and Cronin 2000, Walker et al. 1987a) and by thermokarst (Walker and Everett 1987). There have been several indirect effects: Dust shadows on the leeward side of roads and gravel pads can accelerate snow melt and alter the condition of plant communities (Walker and Walker 1991). Drifted snow on the windward sides of roads can delay snowmelt and the damming effects of roads can create impoundments (Kertell and Howard 1997, Walker 1996). Almost 3% of the area of current oil fields is covered by gravel, although newer developments require only about one-tenth the amount of gravel fill that was required for the earliest oil fields (Gilders and Cronin 2000). The area affected by thermokarst and impoundment associated with gravel fill is approximately double the area covered by gravel.

Because raptor densities are concentrated inland from existing oil fields especially along the Colville River, which has one of the highest densities of nesting raptors anywhere on Earth. Past development has probably not measurably affected those populations. Rough-legged hawks (*Buteo lagopus*) and ravens (*Corvus corax*) might have benefited slightly from development because they use anthropogenic structures for nest platforms (Day 1998, Ritchie 1991).

The power lines that are ubiquitous in older oil fields cause minor mortality of migrating birds in other regions (e.g., Faanes 1987). One study detected 4 collisions and reported 31 dead birds over 2 years (Anderson and Murphy 1988). Correcting for detection bias, (dead birds scavenged before being found), Anderson and Murphy (1988) estimated 1 collision for every 1,000-7,000 flights across the power line, which was at the low end of reports from other studies of bird collisions with powerlines. Nonetheless, if rare species or pre-breeding adults are among the colliders, these could be effects of importance for those particular species. Individuals from fifteen avian species were identified; no species was represented by more than three individuals (B. Anderson, ABR Inc., unpublished data). Five of the carcasses were identifiable only as waterfowl. Potentially sensitive species represented in the sample of carcasses included long-tailed ducks (three individuals), and an unidentified eider. Given the small numbers representing any individual species, power line collisions are unlikely to represent an important source of mortality in the oil fields. This source of mortality is likely to remain confined to the core areas of the Prudhoe Bay and Kuparuk oil fields if new fields continue the recent trend of placing power lines on pipeline supports or burying them in roads.

Tundra Ponds

Spills that contaminate tundra ponds could cause significant damage to the ponds and to birds that use them. If oil becomes trapped in sediments, preventing weathering, the effects on organisms can persist as fresh oil emerges. Miller and colleagues (1978) studied tundra ponds affected by natural oil seeps and experimental spills. Zooplankton was virtually eliminated, although phytoplankton productivity that was reduced initially returned to normal. Recovery can take several years, however. Data from experimental spills suggest that recovery could be enhanced by the addition of nutrients to stimulate the growth of oil-degrading organisms (Bergstein and Vestal 1978, Horowitz et al. 1978).

Predators

Birds and their nests in the oil fields have a suite of predators, the most important of which are arctic foxes, glaucous gulls (*Larus hyperboreus*), grizzly bears, and ravens. The populations of all of those predators have increased in the oil fields (Burgess 2000, Burgess et al. 1993, Eberhardt et al. 1982, Truett et al. 1997), most likely because of the increase in garbage. Gull populations are on the rise throughout the Arctic (Bowman et al. 1997, Kadlec and Drury 1968, Mallek and King 2000, Vermeer 1992), however, so it is not clear whether the increases in the oil fields are part of a global pattern or associated with local changes caused by oil development (Day 1998). Day (1998), however, cites numerous accounts of heavy use on the North Slope of landfills, including those in the oil fields, for foraging by glaucous gulls.

Bird Species of Special Concern

Loons

Pacific loons (*Gavia pacifica*) sometimes nest on the shores of impoundments (Kertell 2000), so increases in impounded water in developed areas could be beneficial to this population if productivity on impoundments is similar to that in natural wetlands. Kertell and Howard (1997) were unable to detect important limnological differences between natural wetlands and impoundments, and Kertell (1996) found little difference in adult foraging behavior or provisioning of chicks for loons that fed on natural ponds or impoundments. Nest success on a study site in the Kuparuk oil field averaged 60% ($n = 19$) (Moiteret et al. 1996), and nest success in the Prudhoe Bay field was 41% and 33%, respectively, for natural ponds and impoundments (Kertell 1996). Nest success of Pacific loons on the Yukon-Kuskokwim delta in southwestern Alaska was 32% (Petersen 1979), slightly lower than that in the oil fields. Overall productivity (fledged young per nesting attempt) of Pacific loons was comparable at Prudhoe Bay to that of arctic loons in Scandinavia (Gotmark et al. 1989, Kertell 2000). Neither loon density nor trend estimates exist for the oil fields, however, making it impossible to determine whether changes in habitat have influenced the Pacific loon population within the oil fields.

Much less is know about yellow-billed loons (G. *adamsii*) but Alaska's North Slope, particularly the National Petroleum Reserve-Alaska, is a major breeding area for this species, which is being considered for listing under the Endangered Species Act.

Shorebirds

Semipalmated sandpipers (*Calidris upsilla*), pectoral sandpipers (*C. melanotos*), and red-necked phalaropes (*Phalaropus lobatus*) are the most widespread and abundant breeding shorebirds across the North Slope, with densities exceeding 10 nests per km^2 (26 nests per mi^2) in the National Petroleum Reserve-Alaska (Cotter and Andres 2000). The North Slope is a relatively important breeding area for red phalaropes (*P. fulicaria*) (Cotter and Andres 2000, FWS 1986), bar-tailed godwits (*Limosa lapponica*), stilt sandpipers (*C. himantopus*), and long-billed dowitchers (*Limnodromus scolopaceus*) (Cotter and Andres 2000). Dunlins (*Calidris alpina*) are locally important and were intensively studied during the 1960s near Barrow (Pitelka et al. 1974). Buff-breasted sandpipers (*Tryngites subruficollis*) are not abundant, but about half of the world's population nests on the North Slope, entirely within the area of known or probable oil and gas resources (Audubon Alaska 2001, Gottthardt and Lanctot 2002, Lanctot and Laredo 1994). This species is also being considered for listing under the Endangered Species Act.

Shorebird populations appear to be stable in the oil fields, except for dunlins, which have declined there (Troy 2000) and elsewhere on Alaska's North Slope (Norton in Troy 2000). It is possible that the population losses are the result of factors outside the oil fields. Habitat declines on wintering and staging areas in Asia (Hanawa 1985, Melville 1997, Tobai 1997) could be the cause of the Alaskan declines (Troy 2000).

Two mechanisms have been examined: habitat alteration, which causes direct or indirect effects, and reduced nest success associated with predation. Direct alteration of habitat displaces individuals from locations where they might otherwise nest. Secondary effects, including changes in drainage patterns, thermokarst, deposition of dust, and disturbance associated with activity on roads, can displace additional individuals. Shorebird densities are lower near roads and gravel pads than in more distant areas (Connors and Risebrough 1979, TERA 1993a, Troy and Carpenter 1990), but densities are higher on the leeward sides of roads than elsewhere, suggesting that dust shadows could create conditions attractive to shorebirds (TERA 1993a). Both Meehan (1986) and TERA (1993a) estimated that 5% of shorebirds were displaced from preferred nesting areas by the direct or secondary effects of oil-field facilities. The impact of such displacement on population dynamics is unknown, however, because potential limiting effects of nesting habitat are poorly understood on Alaska's North Slope. Attempts to assess tertiary effects, such as habitat fragmentation, have produced contradictory results (Meehan 1986, TERA 1993a).

Troy (1996) reported that semipalmated sandpiper abundance was correlated with nesting success two years before, suggesting that recruitment might play an important role in regulating this population in the oil fields. Few estimates of nest success for other sites in Alaska are available for comparison. There is evidence that nesting success for other ground-nesting birds is unusually low in the oil fields (Anderson et al. 2000, Sedinger and Stickney 2000), and that, combined with Troy's (1996) results, suggests that increased predation in the oil fields is affecting local shorebird populations.

Shorebird populations have probably been affected by the loss in food supply caused by contamination of wetlands by reserve pits (West and Snyder-Conn 1987). West and Snyder-Conn (1987) demonstrated that invertebrate diversity and abundance were reduced in wetlands within 25 m (80 ft) of reserve pits. However, because reserve pits are no longer used for disposal of drilling waste and because existing reserve pits are being emptied, the outlook is improved.

Tundra Swan

Tundra swan (*Cygnus buccinator)* populations have increased in Alaska (Conant et al. 2000) after their over-harvesting in the early part of the twentieth century (Banko and McKay 1964). The rate of increase in the Kuparuk oil field between 1988 and 1997 (Ritchie and King

2000) exceeded that in other parts of Alaska (Conant and Groves 1997). There are caveats, however. Alaska's North Slope tundra swans, including those that inhabit the oil fields, winter on the east coast of the United States; those that breed in southwestern Alaska winter west of the Rocky Mountains (Bellrose 1980). Thus, tundra swans in the two regions experience different winter conditions. Additionally, climate warming has been pronounced on the North Slope, producing longer frost-free periods during the breeding season (Lachenbruch and Marshall 1986), which might have disproportionately benefited swans there. Thus, if there have been negative effects of oil-field development on tundra swans, they have been insufficient to prevent the rapid growth of the population during the past decade.

As with other species of birds, loss of habitat could reduce swan densities in the oil fields. Given the large territories (Ritchie and King 2000) and resulting low densities of breeding swans throughout their range, however, it is unlikely that the loss of less than 5% of potential breeding habitat has substantially affected breeding swans in the oil fields. Disturbance associated with facilities might be more important than habitat loss, because swans are sensitive to human disturbance at considerable distances (greater than 500 m [1600 ft]) (Monda 1991). Tundra swan broods have been reported to avoid some areas within 100-200 m (330-660 ft) of roads, although habitat use outside the breeding season did not appear to be affected by roads (Murphy and Anderson 1993). Ritchie and King (2000) concluded that oil-field facilities had little influence on distribution of tundra swan nests because the mean minimal distances from swan nests to structures were less than the mean minimal distances between nests (Stickney et al. 1994), so territorial spacing is more important to breeding distribution than is proximity to artificial structures.

Predation does not seem to have influenced nest success in the oil fields (83%) (Murphy and Anderson 1993), which was comparable to that for tundra swans nesting in Arctic National Wildlife Refuge (76%) (Monda et al. 1994).

Black Brant

Nest success of black brant in the oil fields has been chronically low, ranging from 44% to 55% (Sedinger and Stickney 2000), in contrast to that in other colonies where nest success is typically near 80% (Barry 1967, R. Sedinger, unpublished material). Low nest success is associated with high predator populations in the oil fields. Modeling of this population suggests that oil-field populations are not sustainable at such inadequate nest success and could represent a sink population (Sedinger and Stickney 2000). Thus, high predator populations associated with human activity in the oil fields likely represent the greatest harm to nesting brant in the region.

Black brant nesting in the oil fields are a relatively small proportion (less than 2%) of the entire breeding population for this subspecies (Sedinger et al. 1994, Sedinger and Stickney 2000), although many brant broods from the Colville River Delta use the oil fields after hatching. Brant breeding in the oil fields and in the delta increased several-fold between 1982 and 1992 (Sedinger and Stickney 2000), supporting the view that the growth has been sustained by immigration from other areas.

Brant nest colonially or semi-colonially (Sedinger et al. 1993) and are therefore, less likely to be displaced by oil-field structures unless the facilities are placed on or immediately adjacent to nesting concentrations. Facilities do not seem to have displaced nesting brant (Murphy and Anderson 1993, Stickney and Ritchie 1996). The largest nesting concentrations in the oil fields occur on Howe and Duck islands, 5 km (3 mi) and a few hundred meters, respectively, from the Endicott causeway. Similarly, large numbers of brant broods use the salt marsh within 0.5 m (1.6 ft) of the Oliktok long-range radar site (Sedinger and Stickney 2000). During nesting and brood rearing at these sites, brant responded to humans at distances of less than a few hundred meters (Murphy and Anderson 1993). Brant also responded to 12% of vehicles that passed within 300 m (980 ft), although those responses lasted less than 5 min (Murphy and Anderson 1993) and likely had little effect on their nutritional status. Observations of color marked and radiotagged brant broods provided no evidence that roads or other oil-field facilities impeded movement from nests to brood-rearing areas (Stickney 1996). Brant goslings in the oil fields were actually larger than those from the Yukon-Kuskokwim delta at the same age, implying greater abundance of food in the oil fields (Sedinger et al. 2001).

A long-term color-marking and monitoring program has allowed estimates of annual survival for adult and juvenile brant from the oil fields. The estimates show that adults from the oil fields have similar if not slightly higher survival rates than those from the delta in southwestern Alaska (Sedinger et al. 2001). Juvenile brant from the oil fields survived the first stage of fall migration at higher rates than did those from the Yukon-Kuskokwim delta, probably because of their superior growth conditions (D.H. Ward, U.S. Geological Survey, personal communication).

The North Slope is particularly important as a molting are for black brant. About one-third of the world's population of Pacific black brant assemble in the lakes and tundra north and east of Teshekpuk Lake to molt. During that time they are sensitive to disturbance by aircraft, especially helicopters (Berksen et al. 1992, Tensen 1980, Ward and Stehn 1989). If industrial activity expands into this region in the form of satellite fields without permanent road links, increased air traffic is inevitable. The fact that brant fly long distances to molt in this area strongly suggests it is unusually favorable as a place to molt. This assumption is supported by analyses of the tundra vegetation in this area.

Eiders

Spectacled (*Somateria fischeri*) and Steller's (*Polysticta stelleri*) eiders are currently listed as threatened under the Endangered Species Act, mainly because of their decline in excess of 90% since the 1970s on the Yukon-Kuskokwim delta in southwestern Alaska (Stehn et al. 1993). Threatened status has heightened interest in the North Slope populations, but the historical record is short, and there are no data with which to compare pre- and postdevelopment populations. Spectacled eiders nest at relatively low densities on the North Slope (Ducks Unlimited 1998, Mallek and King 2000), so it is difficult to acquire sufficient censuses to make inferences.

Nesting spectacled eiders do not appear to avoid oil-field structures, although nests appear to be farther from facilities than are those of prebreeding spectacled eiders (Anderson et al. 2000). Nest attendance patterns in the oil fields (Anderson et al. 2000) are comparable to those in the delta (Flint and Grand 1999), indicating that disturbance of incubating females does not reduce nest attendance in the oil fields. Nest success in the oil fields (42%) (Anderson et al. 2000), however, is substantially lower than in the delta (48%, Grand and Flint 1997; 70%, Moran 2000). Low nest success in the oil field is primarily associated with predation (Anderson et al. 2000). Despite the low nest success, the population in the oil fields was stable over 8 years of monitoring (1993-2000) (Anderson et al. 2000), although the relatively short study period and the small numbers recorded (typically fewer than 10 nests) each year make it difficult to discern actual trends. Low nest success is cause for concern, however, and the local population might not be sustainable without regular immigration.

Because common eiders (*Somateria mollissima*) nest predominantly on barrier islands in the Beaufort Sea they have not been close to most oil field activities. One exception was intensive operations in 1983 near Thetis Island, north of the Colville River Delta (Johnson 2000). Nest success on Thetis Island in 1983 (81%) was higher than in other years or at other locations on Alaska's North Slope (less than 45%), possibly associated with removal of arctic foxes from Thetis Island that year (Johnson 2000). Numbers of common eider nests on barrier islands north of the oil fields have generally increased since 1970, possibly as a result of placement of anthropogenic debris on the islands, which eiders use as nesting cover (Johnson 2000). Glaucous gulls are important predators of eider ducklings but there are no data to evaluate the potential effects of increased glaucous gull populations in the oil fields on survival of common eider ducklings in coastal lagoons immediately north of the oil fields (Johnson 2000).

King eiders (*S. spectabilis*) have been studied for a shorter period, but there are no apparent trends in their populations within the oil fields (Anderson et al. 2001). They do not appear to avoid oil field structures (Anderson et al. 2001). Nest success in the Kuparuk oil field averaged 32% from 1993-2000 (Anderson et al. 2001), similar to that of other waterfowl in the oil fields, and consistent with the hypothesis that nest success rates are low in the oil fields.

Lesser Snow Goose

Like black brant, lesser snow geese (*Chen caerulescens caerulescens*), nest on Howe Island and Duck Island near the Endicott Causeway (Johnson 2000). As with other birds nesting in the oil fields, predation appears to be the principal negative effect of oil development. Oil-field-nesting snow geese are less than 1% of the North American winter population (Bellrose 1980, Johnson 2000), but the oil-field population has increased 10-fold since monitoring began in 1980 (Johnson 1980). Snow geese typically rear broods in salt marshes east of the Endicott Causeway and in freshwater and salt marshes west of the causeway. Broods are reared much closer to the nesting area than is normal for most other snow geese, which often move 70 km (40 mi) for brood rearing. The broods did not change their use of brood-rearing areas after construction of the causeway (Johnson 2000). Nest success was generally lower than for snow geese nesting at La Perouse Bay (mean 92%, Cooke et al. 1995) and no eggs hatched in 1991 or 1992, when arctic foxes were present on the island during the normal nest initiation period. Nest success has been low from 1991 through 2001, with complete failure some years (Alaska Audubon 2001). Thus, the population on Howe Island appears to be a sink.

The North Slope of the Arctic National Wildlife Refuge supports more than 60% of the Pacific population of lesser snow geese during fall premigratory staging (Robertson et al. 1997), so significant effects would accumulate if industrial development were to spread to that area, accompanied by increased aircraft traffic.

Conclusions and Projections of Future Effects

Because of higher predator densities, increased predation on nests is the most apparent effect of oil development on birds that nest in the oil fields. Reduced nest success is sufficient in some cases to cause population declines, so the apparent stability of some oil-field populations is presumably the result of immigration. As industrial activity spreads into new areas, the amount of sink habitat will increase. Placement of oil-field facilities does not appear to have reduced overall densities in the oil fields, although some shorebirds do exhibit local displacement away from facilities and roads. Of course, the direct loss of habitat caused by placement of gravel fill could have reduced numbers, but the small areas actually covered, combined with the low densities of breeding birds, make it impossible to measure that effect.

Similar changes are to be anticipated in newly developed areas, and it appears that controlling anthropogenic food sources that could enhance predator populations will be essential to minimizing effects of predation on birds. One important unknown is how the expanded use of 3-D seismic exploration will affect birds: To the degree that this activity affects vegetation, it might affect breeding birds in areas of new development.

An important consideration is that new development in the foothills of the Brooks Range could impinge on raptor species' nesting and hunting habitats. Assessment of the effects of human activities on breeding raptors has produced mixed information (Andersen et al. 1990, England et al. 1995, Schueck and Marzluff 1995, Schueck et al. 2001, Grubb and Bowerman 1997). Andersen et al. (1990) detected shifts in home ranges of less than 1 km in response to military training activity in southern Colorado. Schueck and colleagues (2001), however, detected little effect on the number, distribution, or behavior of raptors in the Snake River Birds of Prey National Conservation Area in response to military training activity, although they noted that raptors responded to firing of live ammunition. When effects of weather were removed from the analysis, effects of military activity on raptor distribution were further reduced (Schueck and Marzluff 1995). England and colleagues (1995) documented reduced fledging success for Swainson's hawks (*Buteo swainsoni*) in urban relative to rural areas of the Central Valley of California. That research group attributed reduced fledging success of urban nests to the distance the birds had to travel to foraging areas rather than to disturbance around nest sites. Grubb and Bowerman (1997) reported that fixed-winged aircraft elicited a response from nesting bald eagles less than 30% of the time at distances greater than 500 m (1,600 ft). Bald eagles flew less than 5% of the time in response to those disturbances. Helicopters less than 500 m (1,600 ft) from nests, in contrast, elicited flight responses about 10% of the time (Grubb and Bowerman 1997). It is difficult to evaluate is the potential effect of 3-D seismic exploration on prey for raptors, such as ptarmigan (*Lagopus lagopus*) and arctic ground squirrels. Direct effects on these populations are unlikely, but any changes in vegetation and soils over large areas could reduce habitat quality for prey, thereby reducing their populations. Given the relatively small effects of large disturbances and the location of raptor nests on cliffs and steep lakeshores and river banks, it should be possible to conduct oil development in the foothills of the Brooks Range with small effects on nesting raptors, especially if aircraft and other human activities near nests are regulated.

Future industrial development will likely occur in a warming climate that would probably affect timing and success of reproduction of many bird species. Tundra vegetation also is likely to change. Shrubs are likely to increase at the expense of herbs, favoring some species over others. Not enough information is available at present to evaluate how likely such effects are to occur and how they will accumulate with the effects of oil and gas activity.

Findings

- Shifts in nesting distribution of shorebirds have occurred in response to oil-field facilities but because of insufficient information the committee cannot determine whether the displacement has affected oil-field populations.
- Inadequate disposal of garbage has resulted in artificially high densities of gulls, ravens, and mammalian predators in the oil fields. The resulting increased predation of birds' nests and young has likely made some oil-field populations dependent on immigration from more productive populations elsewhere. That is, nesting areas that might have been source habitats have become sink habitats. However, population studies alone cannot reveal such effects.
- Future development in the foothills of the Brooks Range could affect nesting raptors.
- If development moves into the Teshekpuk Lake area of the National Petroleum Reserve-Alaska, molting waterfowl could be adversely affected, especially brant.
- A major oil spill associated with shoreline or offshore oil development would endanger molting flocks of waterfowl in nearshore lagoons.

FISH

The life cycles of freshwater and diadromous fishes on the North Slope are adapted to the region's long winters and low productivity (Craig 1984, 1989; Power 1997). After break-up, fish move quickly during the brief summer into many habitats, often at great distances from the wintering area. For example, arctic cisco (*Coregonus autumnalis*) from the Colville River can return to spawning areas more than 600 km (370 mi) from the wintering area (Gallaway and Fechhelm 2000). Locating a suitable wintering area at the end of the summer is critical to survival. Craig (1989) estimated that substantially less than 5% of stream habitat remains available to fish by late winter. These widespread movements and the greatly restricted area of habitat available to fish in winter make many of these species highly vulnerable to the effects of oil and gas exploration and development.

Nearly 40 species of fish are routinely caught during studies in freshwater and nearshore habitats of the North Slope (Bendock 1979, Cannon et al. 1987, Craig and Haldorson 1981, Fechhelm et al. 1984, LGL Alaska Res. Assoc. 1990-1996, Moulton et al. 1986, NSB 2001). Others are caught occasionally, but they tend to be rarer or associated with offshore marine areas.

Seventeen of the frequently occurring species commonly enter the subsistence harvest. Arctic cisco and broad whitefish (*Coregonus nasus*) have the highest subsistence value. An average of 18,500 kg (40,800 lb) of arctic cisco was harvested annually from the Colville River delta each fall from 1985 to 1998, with an additional 3,200-4,000 kg (7,100-8,800 lb) taken near Kaktovik (Craig 1987, Fuller and George 1997). The broad whitefish harvest by North Slope villages is estimated to be more than 28,000 kg (62,000 lb) annually (Fuller and George 1997, Hepa et al. 1997).

Fishes along the North Slope have three principal life histories: freshwater, diadromous, or marine. Diadromous fishes move between fresh water and the sea during their lives. The term includes *anadromous* species, which spawn in fresh water and grow in the sea; *catadromous* species, which do the reverse; and those species that can spend substantial amounts of time in either environment, but not necessarily mainly to reproduce or mainly to grow. The term *diadromous* is applied to ciscoes, whitefishes, and Dolly Varden char (*Salvelinus malma*) that migrate each year between freshwater and coastal habitats (Gallaway and Fechhelm 2000). Most freshwater species spend their entire lives in rivers and lakes of the North Slope and generally avoid saline waters, although some, such as arctic grayling (*Thymallus arcticus*) and round whitefish (*Prosopium cylindraceum*) move down river to enter low-salinity estuarine waters during early summer.

Diadromous species, such as Dolly Varden char, arctic cisco, broad whitefish, and least cisco (*Coregonus sardinella)* migrate each summer between upriver overwintering areas and feeding grounds in coastal waters. That group is more abundant along the Beaufort Sea coast than along the northeastern Chukchi coast, possibly because of a lack of large rivers and because of the Chukchi's less-productive coastal region (Fechhelm et al. 1984).

Most marine species inhabit deeper offshore waters and are rarely reported in the North Slope coastal zone. Notable exceptions along the Beaufort Sea coast are arctic cod, fourhorn sculpin (*Myoxocephalus quadricornis*), and arctic flounder (*Pleuronectes glacialis*), which specifically migrate into shallow, low-salinity coastal waters and estuaries during summer. Those species, along with capelin (*Mallotus villosus*) and Pacific herring (*Clupea harengus pallasi*), also dominate the fish biota along the Chukchi Sea coast (Fechhelm et al. 1984).

Diadromous and Freshwater Fishes

Diadromous fishes in the Beaufort Sea exist in two major population centers: the Mackenzie River system of Canada in the east and the Colville River and Arctic Coastal Plain systems of Alaska in the west (Craig 1984). Most of the major river systems along the 600 km (370 mi) coastline between the Mackenzie and Colville rivers originate in the Brooks Range (Craig and McCart 1975). The rivers are shallow and provide little over-wintering habitat except for that associated with warm-water perennial springs (Craig 1989). Dolly Varden char and arctic grayling are the two principal species that inhabit those mountain streams, although lakes associated with the drainages can contain lake trout (*Salvelinus namaycush*), arctic char (*Salvelinus alpinus*), and arctic grayling. Ninespine sticklebacks (*Pungitius pungitius*) also are prevalent in drainages within the western mountain streams. Small runs of pink salmon (*Oncorhynchus gorbuscha*) occur in the Sagavanirktok and Colville rivers, and spawning populations of chum salmon (*O. keta*) inhabit the Colville and Mackenzie rivers (Craig and Haldorson 1986, Moulton 2001). The remaining salmon species consist of individuals from southern populations (Bering Sea) that are incidental visitors to the Beaufort Sea (Craig and Haldorson 1986). Three species—arctic cisco, broad whitefish, and arctic grayling—are examined here in detail. These three use the complete range of habitats affected by the North Slope oil and gas development, and at their various life stages they are vulnerable to the consequences of development. The few diadromous species found along coastal region of the northeast Chukchi Sea likely originate from large river systems in the southeast Chukchi Sea or along the Beaufort Sea (Fechhelm et al. 1984).

Arctic Cisco

Arctic cisco in the Alaskan Beaufort Sea originate from spawning grounds in the Mackenzie River system of Canada (Gallaway et al. 1983, 1989). Fry emerge by spring ice break-up in late May to early June and are swept downstream to coastal waters, where they begin feeding in the brackish waters near the Mackenzie delta. Young-of-the-year are transported away from the Mackenzie region by wind-generated currents. In years with predominant easterly winds, some young-of-the-year are transported westward to Alaska by wind-driven coastal currents (Colonell and Gallaway 1997, Fechhelm and Fissel 1988, Fechhelm and Griffiths 1990, Gallaway et al. 1983, Moulton 1989, Schmidt et al. 1991, Underwood et al. 1995). They arrive in the Prudhoe Bay area from mid-August to mid-September. In summers with strong and persistent east winds, enhanced westward transport can carry the fish to Alaska's Colville River where they take up winter residence. After entering the Colville River, they return to the river every fall for wintering until the onset of sexual maturity at about age 7, at which point they migrate back to the Mackenzie River to spawn (Gallaway et al. 1983). Juvenile arctic cisco are abundant enough to support a commercial fishery in the Colville River and a subsistence fishery at Nuiqsut (George and Kovalsky 1986, George and Nageak 1986, Moulton 1997, Brower and Hepa 1998).

Possible Accumulation of Effects and Likeliness of Occurrence

Recruitment of young arctic cisco into the Alaskan Beaufort Sea is a function of wind-generated coastal currents, so facilities that interrupt the movement of fish along the coast could lead to reduced recruitment. The presence of multiple similar structures would cause effects to accumulate. To affect recruitment, a structure would modify the coastal habitat in such a way as to hinder young arctic cisco from reaching the Colville River, the most suitable wintering area. The hindrance could result from modifying the coastal environment so that westward movement is delayed enough that they fail to reach the Colville River in the recruitment year. The available data indicate that arctic cisco recruitment has not been affected by existing causeways (NSB/SAC 1997).

In an environment where heat is at a premium, the warm coastal waters are important to diadromous fishes (Craig and Haldorson 1981). Facilities that disrupt this narrow coastal band could disrupt the coastal movements of arctic cisco and other diadromous species (Hachmeister et al. 1991, Hale et al. 1989). Any future operations that discharge warm water could serve as attractants that would prevent fish from moving to wintering areas at the proper time. The potential for effects to accumulate arises when multiple facilities affect the same populations of fish.

Broad Whitefish

Broad whitefish are common in lakes and streams of the Arctic Coastal Plain, most abundantly in large rivers, such as the Colville, Ikpikpuk, and Chipp rivers, that have deep, low-velocity channels and a multitude of connected lakes. They are also in the Sagavanirktok River, but its steeper channel gradient and low number of connected lakes limit the population. During summer, some broad whitefish enter small tundra streams.

The fish use a variety of habitats through their life cycle. Spawning is in deep portions of large rivers in the fall. In the Mackenzie River in Canada, broad whitefish spawn in the lower river just upstream of the marine influence. Similarly, the anadromous population in the Colville River spawns in the main river upstream of the delta. Bendock and Burr (1986) identified a prespawning migration in August. During the spring flood, age-0 and juvenile broad whitefish enter a variety of available habitats, including seasonally flooded lakes, lakes connected to stream systems, river channels, and coastal areas. Fish that use perched lakes remain in the lakes until they reach maturity, then return to the river in the spring of the year in which they will spawn. Broad whitefish that do not enter perched lakes either enter the coastal region and adjacent small drainages to feed or remain within the river system to feed in low-velocity channels, tapped lakes, or drainage lakes. In fall, they move out of the shallow feeding areas and return to the deep wintering areas in the main river or lakes. Fish from the Sagavanirktok River population move through the Prudhoe Bay coastal region and enter lakes attached to small drainage systems (Morris 2000).

During summer, broad whitefish are distributed throughout the drainages and coastal plain water bodies. The highest abundance in coastal marine waters is near river deltas (Furniss 1975, Griffiths et al. 1983, Moulton and Fawcett 1984, Moulton et al. 1986, Schmidt et al. 1983), although large fish move at least between the Colville River and Prudhoe Bay region. When they are in coastal waters, broad whitefish show a strong preference for nearshore habitats, appearing only rarely offshore or near barrier islands (Craig and Haldorson 1981, Moulton et al. 1986).

The main overwintering areas in the Colville River are upstream from the Itkillik River. Most broad whitefish leave the delta after ice forms and move upstream beyond the influence of salt water. In the Sagavanirktok River, wintering areas have been identified in both the east and west channels within 20 km (12 mi) of the river mouth (Morris 2000).

Possible Accumulation of Effects and Likeliness of Occurrence

Because of the wide range of habitats used by broad whitefish populations in the Sagavanirktok and Colville rivers, the potential for effects to accumulate is high. They use nearly all stream systems between Barrow and the Sagavanirktok River, they enter a large number of lakes associated with the streams, and they move widely along the coast, ranging as far east as the Canning River. As a result, they are vulnerable to facilities that change the distribution of fresh water and the coastal nearshore band. Because many rear in lakes, they are vulnerable to excessive water withdrawal and the introduction of contaminants.

Arctic Grayling

Arctic grayling is the second-most-widespread freshwater fish on the North Slope, after ninespine stickleback. It occurs in most stream systems and in many lakes (Moulton and George 2000). Grayling typically overwinter in deep areas within larger rivers—the Colville, Kuparuk, Sagavanirktok, and Canning. Wintering areas are limited or nonexistent in smaller tundra streams (Hemming 1993). During or after ice break-up, adult grayling move into tributary streams for spawning. Streams with sand or gravel substrates seem to be most heavily used.

After spawning, adults disperse to summer feeding areas, moving downstream in the tributary to feed on drift insects, moving into lakes, or returning to the main river. Grayling embryos hatch after about three weeks. Young-of-the-year (age-0) grayling feed in tributary streams until late summer, then move into the main river for wintering. Juveniles, which do not participate in spawning migrations, move in spring from wintering areas into small streams, lakes, or shallow areas within the main river to find suitable feeding areas.

As with most arctic freshwater fish, arctic grayling are strongly limited in abundance by the availability of wintering habitat. Many streams across the Arctic Coastal Plain are devoid of grayling or contain only a few juveniles because they are far from suitable wintering areas and lack dispersal routes that allow free passage during both spring and late summer.

Possible Accumulation of Effects

Disruptions to flow patterns that affect arctic grayling movements can affect survival, and the proliferation of roads and culverts across wetlands and streams creates the potential for effects to accumulate. Delays in the upstream spawning migration were common in the early stages of oilfield development, when culverts were too small to handle break-up flows. Road-crossing and culvert designs now include fish passages, so effects should be less than in the early years of development.

The distribution of arctic grayling has expanded because of habitat alterations in the oil-field region. Some of the large, deep gravel pits excavated for oil-field construction material filled with water after abandonment to form large artificial lakes that provide abundant wintering habitat. Hemming (1988) reported that a mine site connected to the Sagavanirktok River contained 88 times more water than the largest wintering areas reported within the river itself. Two of the deep gravel pits were connected to small tundra streams that appeared to contain suitable spawning and rearing habitat but lacked wintering areas. Arctic grayling of various ages were introduced over several years and eventually developed reproducing populations (Hemming 1995). The cumulative effect of these large gravel pits is to increase the available freshwater wintering area. It is not known whether the amount of habitat added by the gravel pits outweighs possible loss of habitat attributable to hampered migration caused by roads and pads, but with the recently increased attention to structural design it is likely that most of the migration problems have been solved.

There is a reasonable amount of information on fish-passage problems and ways to mitigate them (Ott 1993). The rehabilitation and success of habitat restoration in many of the North Slope gravel pits are well documented (Hemming 1988, 1993, 1995, Hemming et al. 1989).

Effects in Freshwater Systems

Effects in streams and lakes can accumulate through disruption of drainage patterns combined with water withdrawal and contamination. Hershey and colleagues (1999) demonstrated that the landscape controls biological interactions in lakes through facilitating or limiting fish dispersal. Activities that affect dispersal through alterations to drainage patterns can ultimately affect the assemblage of fishes in different habitats. Water withdrawals affect the amount of water present during winter, which can affect fish survival.

Drainage Patterns

Drainage patterns are altered by the construction of roads or pads in or across wetlands or drainage areas. To date, 2,338 ha (5,777 acres) of gravel pads, including more than 875 km (544 mi) of roadways, have been constructed in association with oil-field development on the North Slope (Chapter 4). Much of the gravel fill has been in wetlands where cross-pad drainage has been blocked by road construction. During spring ice break-up, there is substantial flow across expansive wetlands into lakes and streams. When long stretches of gravel road interrupt flow, the difference in water surface elevation from one side of the pad to the other can produce high-velocity water flow in the cross-pad drainage structures, usually culverts, that can inhibit upstream fish movements and delay migration to various summer habitats. The delays are particularly problematic for arctic grayling, which spawn shortly after break-up and often undertake long, rapid migrations from wintering areas to spawning sites.

An opposite effect can occur in mid- to late summer when stream flow is low. Fish that disperse during or after break-up must leave small drainages and shallow lakes to reach wintering areas before those waters freeze because there are often limited or no opportunities for overwintering within the habitats used for summer feeding. Fish that cannot leave will freeze. An inadequate number or improper placing of culverts or modifications to the stream bed can cause flow to go below the surface or to be spread too shallow to allow downstream movement when flow levels are reduced in late summer.

Large quantities of gravel have been used to construct the oil-field infrastructure. In the early period of development and pipeline construction, much of the gravel was obtained from gravel deposits within floodplains. But concerns arising from this practice prompted the FWS to study the effects of floodplain gravel mining on the floodplains physical and biotic processes (Woodward-Clyde Consultants 1980). The study identified numerous examples of habitat modification, including increased channel braiding, loss of wintering areas, spreading of flow, and restriction of fish movements, including mortality caused by stranding. The study also set forth guidelines for gravel mining that minimize floodplain damage (Joyce et al. 1980). In response to agency concerns, and results of the FWS study, new gravel mines were primarily in upland sites during the 1980s. Some of these were flooded when mining ceased and used as reservations, with the long-term goal of establishing aquatic habitat. Recently, some new mines have been in floodplains, again following established guidelines.

Water Withdrawal

Use of fresh water has increased in recent years because of expanded oil-field development and increased exploration. In the early years of exploration, water was obtained from any source, including rivers during winter. Bendock (1977, as cited in Winters et al. 1988) documented water withdrawals from the Sagavanirktok River that depleted water in wintering areas and increased mortality to fish in the area. Much of the water needed in the established oil fields is now obtained from reservoirs that are replenished with runoff during spring ice break-up; most of the water used in exploration is from lakes.

Ice thickness has a great influence on the distribution of fish in lakes across the Arctic Coastal Plain. Most lakes in the existing development area between the Colville and Sagavanirktok rivers are less than 2 m (6.5 ft) deep, few fish are present and effects have been minimal. As development spreads into regions with deeper lakes, such as the Colville delta and the eastern part the National Petroleum Reserve-Alaska there is greater potential for having fish populations within lakes. Under current Alaska Department of Fish and Game (ADF&G) policy, water withdrawals from fish-bearing lakes are limited to 15% of the estimated minimum winter water volume. This policy was adopted to allow some water use while preserving most of the water for wintering fish, and the criterion was set arbitrarily because there were no data to support a different use. Fish populations in lakes subjected to this maximum allowable withdrawal appear to be unaffected, but data on consequences are limited, and there has been no research to determine the effects of withdrawals on populations of invertebrates in the lakes or on vertebrate food supplies.

The current practice for ice road construction is to permit withdrawals from a large number of lakes along a desired route, then to allow the ice road contractor to draw from the nearest suitable lake. This allows for maximum construction flexibility, but it complicates the tracking of withdrawal volumes: Much more water is permitted for withdrawal than is used. Between 1998 and 2001, for example, Phillips Alaska obtained annual permits for withdrawals of more than 8.3 billion L (2.2 billion gal), but used less than 908 million L (240 million gal) in any given year (Table 8-2).

Table 8-2 Phillips Alaska Water Permits

Winter Year	Lakes Permitted	Withdrawal Limit (million L)	Total Used (million L)	Percentage Used
1998-1999	26	8,477.4	771.1	9.1
1999-2000	41	8,468.7	886.2	10.5
2000-2001	24	8,944.1	344.5	3.9

Source: Phillips Alaska, Inc., data files submitted to Alaska Department of Natural Resources.

For lakes that do not support wintering fish, there is essentially no current regulation of winter water withdrawals, and the amount estimated to be present during summer is typically set as the withdrawal limit. Because ice thickness grows to 1.2-1.5 m (4-5 ft) by the time withdrawals are needed in January through March, there is substantially less water available than the permitted amount, thus the full amount is not really available for use and the actual withdrawal is considerably less than that permitted. This practice essentially allows withdrawal of all remaining unfrozen water in the lake at the time of withdrawal. The effects of such withdrawals on lake flora and fauna have not been analyzed. Effects on invertebrates are not likely to be significant because during winter most invertebrates inhabiting shallow lakes are in freeze-tolerant resting stages. The potential effects of reduced water levels on vegetation and waterfowl nesting or feeding have not been evaluated.

An additional issue associated with water withdrawals from fish-bearing lakes is the potential to remove fish during pumping. In recent years, as construction of ice roads has increased in the vicinity of Nuiqsut, residents have reported finding fish frozen into the roads. Contracts issued for ice road construction specify that water is to be screened to avoid removing fish, but contractors sometimes fail to install screens. In some cases, sampling to identify the presence of fish before water withdrawal used gear that was not appropriate for detecting smaller species, such as ninespine stickleback and Alaska blackfish (*Dallia pectoralis*). The problem can be aggravated when lighted shacks are placed over the hole from which water is withdrawn.

Ninespine stickleback, in particular, are drawn to the light, then are sucked up with the water and spread on the road. Procedures have been adopted recently to prevent taking fish with water for road construction.

Seismic Effects

When seismic exploration was conducted with explosives, there was a great potential for harming fish that were exposed to large, rapid changes in ambient pressure. The advent of vibrating equipment has reduced concern, because the energy it generates is much less than that generated by explosives. The ADF&G blasting standards require that the instantaneous change in pressure resulting from any explosion must remain below 0.02 megapascals (MPa, 2.7 psi). Results of a recent field test involving vibrators on ice, over water indicate that peak pressure changes below a vibrator (under 1.2 m [4 ft] of ice) can be as low as 0.01 MPa (1.57 psi). In addition, the energy velocity appears to be many times slower than velocities known to harm fish. Peak sound pressure levels associated with vibroseis exploration, calculated at 7.3 m (24 ft) from the source, appear to be about 12 dB lower than sound pressure levels associated with airguns. When converted to energy, the vibroseis machines transfer many times less energy to the water than do airgun arrays (W. Morris, ADF&G, personal communication, 2002). The effects of summertime seismic exploration with airguns on coastal and marine fish in the Beaufort Sea have not been investigated.

Coastal Development

Coastal development that poses the greatest risk of causing effects that accumulate in nearshore habitats includes facilities that change physical conditions that are important to nearshore biota. Such structures include causeways that modify water temperature and salinity.

Two major causeways have been built into the nearshore region to support oil-field activities (Table 8-3). The Prudhoe Bay West Dock was built in the winter of 1974-1975 primarily to support off-loading of large modules used to develop the field; it was modified in 1981 to support the intake structure for the Prudhoe Bay waterflood facility to supply water needed for injection into the oil reservoirs. The causeway runs from the east end of Simpson Lagoon to the west entrance to Prudhoe Bay. The second major causeway, in the middle of the Sagavanirktok River delta, was built to support facilities for the Endicott oilfield.

Accumulation of effects is a concern when multiple causeways affect the same fish population. The migratory stocks found along the Beaufort Sea coast are likely to encounter multiple causeways during their annual summer feeding movements. From the late 1970s to late 1980s, there was substantial concern over the potential effects of the two long causeways to migrating fishes, especially for the integrity of the nearshore band of relatively warm, low salinity coastal water that is used by migrating fish Craig (1984). Causeways built perpendicular to shore disrupt the east-west flow of the coastal currents, and that can alter fish movements within the band. Permits issued by the U.S. Army Corps of Engineers and the North Slope Borough for causeway construction included stipulations for monitoring the effects of the causeway on fish movements and habitat, among other issues. Initial monitoring studied the West Dock Causeway between 1981 and 1984 and then the West Dock and Endicott causeways between 1985 and 1987. In 1988, the U.S. Army Corps of Engineers concluded that significant harm to habitat had been demonstrated and that further monitoring for effects on fish populations was not required (Hachmeister et al. 2001). Those effects, as summarized Ross (1988), included degradation of habitat quality in the nearshore region, alteration to fish movements and fish use of the Prudhoe Bay area, and changes to fish community structure.

Table 8-3 Causeway Construction, Nearshore Beaufort Sea

Facility	Year	Length of Fill (m)	Notes
East dock	pre-1974	350	
West dock			
Initial dock	1974-1975	1,340	
Emergency extension	1975-1976	1,524	
Waterflood extension	1981	1,125	-18 m breach
Breach Retrofit	1996	-200	at 1,520-1,720 m
Endicott			
Initial causeway	1985	8,000	
Breaches (2)	1986	-60, -150	
Breach retrofit	1994	-200	

Source: U.S. Army Corps of Engineers permitting documents and causeway monitoring reports.

The North Slope Borough, with the advice of its Scientific Advisory Committee, determined that the findings were not supported by the existing data, however, and decided to continue the causeway-monitoring program under its permitting authority. The effects described by Ross (1988) were used to frame a set of hypotheses that were then used to design the monitoring investigations. The North Slope Borough monitoring program focused its investigations on four main issues:

- effects of causeway-induced changes in circulation and hydrography on the migration of young-of-the-year arctic cisco from Canada to the Colville River,
- effects of causeway-induced changes in circulation and hydrography on the nearshore migration corridor used by most species of diadromous fish,
- changes to temperature and salinity of the nearshore habitat and ramifications of those changes to the population of broad whitefish inhabiting the Sagavanirktok River, and
- effects of causeway-induced changes to fish and fish habitat on the fisheries that harvest arctic and least cisco in the Colville River.

The North Slope Borough's program showed that the causeways, particularly the West Dock Causeway, interfere most notably with the eastward movement of juvenile least ciscoes and humpback whitefish moving from the Colville River into the Prudhoe Bay area during early summer (Fechhelm 1999, Fechhelm et al. 1989, Gallaway and Fechhelm 2000, Moulton et al. 1986). Juvenile Dolly Varden char also might be affected (Hachmeister et al. 1991). The movement of young-of-the-year arctic cisco from the Mackenzie River into the Alaskan Beaufort Sea region did not appear to be affected by the causeways (NSB/SAC 1997). Retrofitting of breaches in both causeways in 1994 and 1996 appears to have reduced the effect of the interference to least cisco and humpback whitefish (*Coregonus pidschian*) migrations (Fechhelm 1999).

The causeway studies revealed that, when wind is from the east, a wake eddy forms on the west side of the causeways that allows cold, high-salinity water to reach the surface (Colonell and Niedoroda 1990, Gallaway and Fechhelm 2000). That cell of cold water on the west side of West Dock is the mechanism that most likely impedes fish movements. Because the wake eddy on the west side of Endicott Causeway is offshore of the Sagavanirktok delta, its effects on fish movements are less pronounced. Various researchers have noted that the density of epibenthic fauna (mysids and amphipods), which constitute the main foods of diadromous fish and sea ducks, was particularly high along the west side of West Dock (Feder and McGee 1982, Moulton et al. 1986, Robertson 1991), perhaps as a result of the wake-eddy effect in the lee of the causeway under east winds.

Gallaway and Fechhelm (2000) concluded that fish populations in the region appear to be fluctuating in response to naturally occurring physical phenomena. Effects of the existing causeways have been at least partially mitigated with retrofitted breaches.

In addition to the causeways, large intake pipes are used to withdraw water from the nearshore region. The Prudhoe Bay waterflood facility, constructed in 1981, can supply 350 million L (92.4 million gal) of seawater per day (4.07 m^3/s [5.32 yd^3/s]), with an estimated 2.55 km^3 (0.61 mi^3) to be used over 20 years (USACE 1980). There are also seawater intakes at Endicott (44 million L [11.6 million gal] per day), and Kuparuk (95 million L [25.2 million gal] per day). Monitoring of the intakes and marine bypass systems was conducted after start-up for the Prudhoe Bay and Kuparuk waterflood facilities from 1984 to 1987 to assess entrainment and impingement (Dames and Moore 1985-1987). Fish were rarely observed during the monitoring studies and most of those that entered the system passed successfully. However, approximately 1.5 million fish larvae of 9 species were estimated to have been entrained in the Prudhoe Bay facility in 1985. The intakes were judged to performing as designed and predicted, and monitoring was discontinued after 1987.

Beaufort Sea causeways are among the most intensively studied anywhere. From 1978 to 1997, the West Dock and Endicott causeways were monitored for changes to physical oceanography, coastal processes, sedimentation patterns, fish populations and movements, fish growth, subsistence landings, fish-species diversity, benthic invertebrate populations, epifaunal populations, river hydrology, vegetation, and bird habitat use. Annual reports of the monitoring efforts were produced that summarized the results of the annual investigations. A decade of investigations on oceanographic changes related to the two major causeways was summarized by Colonell and Niedoroda (1990), by Hachmeister and colleagues (1991), Hale and colleagues (1989), and by Niedoroda and Colonell (1990).

The spatial extent of the causeways is relatively limited; the two receiving most of the attention are on either side of Prudhoe Bay. Some of the fish that encounter the causeways, including arctic cisco, however, move between the Colville and Mackenzie rivers at least twice during their lifespan. Some of the least cisco, humpback whitefish, and broad whitefish move between the Colville and Canning rivers for the summer feeding (Fechhelm et al. 2000, Griffiths et al. 2002). The effects of causeways in this region on those fish population could accumulate if the breach retrofits have not completely eliminated movement and habitat changes. Any impacts resulting from the causeways will exist until the structures are removed, or are made porous enough that fish movements are unaffected.

Future Scenario

The potential effects on freshwater systems have become clear during the development of the existing oil fields, so it is likely those effects will be addressed during the design and permitting of new fields and field expansions. The probability for serious effects is low, assuming due diligence by the responsible resource agencies. There will be new challenges, however, as exploration and development practices change. For example, exploration to the east and south will be hampered by the reduced availability of water during winter. In addition, because those areas have more hills and valleys the grades for roads will be more extreme. The current technology based on ice road access is not likely to be feasible in those areas. Similarly, current field development depends on a ready supply of gravel for pad construction. Development of fields in the National Petroleum Reserve-Alaska, where gravel is scarce, will need to rely on other materials for pad construction, and the consequences associated with alternative materials will need to be examined.

Future coastal developments could include more docks and causeways to transport structures or oil on shore. Given the adversarial history of causeway impact assessment, construction of new causeways will be approached carefully with substantial scrutiny by regulatory agencies. Each potential causeway site along the Beaufort Sea coast is unique with respect to currents and the ways that fish use the region. Therefore, the design constraints on each proposed causeway will be site-specific. Nonetheless, long solid-fill causeways are likely to be problematic and therefore are unlikely to be permitted. New docks are likely to be relatively small bulkhead structures near water deep enough to allow barges to approach the shore, so as to minimize the offshore reach of the docks. Where shallow water requires a longer reach, docks will likely have numerous large bridged beaches that allow freer flow of water and minimize the impediments to fish movements.

Findings

- During the early years of development gravel mining for roads and pads often interrupted both ice sheet flow and stream flows, and hence fish movement. The permitting process and the regulatory environment for protecting fish have improved over time and are generally effective. Proper construction and placement of bridges and culverts have greatly reduced effects but have not eliminated them.
- Guidelines for gravel mining and subsequent habitat rehabilitation or enhancement in and near active floodplains have been developed. Since 1989, arctic grayling have been introduced to several of the deep gravel pits that now provide productive fish habitat. One effect of these large gravel pits is to increase the available freshwater wintering area; it is likely that the tradeoff is positive and the negative effects are less than would have occurred if the gravel had been taken from active floodplains.
- The energy produced by vibration equipment used to acquire seismic data is not an issue because the vibrations are below threshold known to affect fish in streams and lakes crossed during the seismic investigations. The potential effects of airguns on Beaufort Sea fish have not been studied.
- Because of a lack of information it is not possible to determine whether biota associated with North Slope lakes are protected by regulations that cap water withdrawal from lakes.

- Existing causeways near Prudhoe Bay do not affect the westward recruitment of arctic cisco into the Colville River and associated rearing areas. Blockage of young least cisco and whitefishes moving eastward from Colville to Prudhoe Bay was demonstrated under certain wind conditions in some years at the West Dock causeway. This blockage has been reduced by the breach retrofit installed in 1996.
- The effectiveness of breach design for existing or new causeways has not been resolved. Breaches are effective, but there is more to be learned about the best or most appropriate design and placement of them. The North Slope Borough's Scientific Advisory Committee recommends that breaches be required in any causeway that extends across the nearshore zone, which seems to be appropriate.
- Seawater intakes have been designed to prevent entrainment and impingement of fishes.
- Large-scale industrial development could harm widely distributed fish, such as grayling, arctic cisco, broad whitefish, and other species in other areas, by interfering with their migration patterns or their overwintering habitat.

Recommendations

- Monitoring of rehabilitated deep gravel pits should continue to evaluate the long-term viability of these sites as aquatic habitat.
- The current baseline of 15% of minimum winter water volume that is allowed to be removed from fish-bearing lakes should be evaluated to determine the degree to which that criterion prevents loss of fish and invertebrates.
- An initial study of the effects of withdrawing water from lakes that have no fish should assess the degree to which current water use affects other biota associated with these water bodies.

OTHER MARINE ORGANISMS

Coastal developments that pose the greatest risk of accumulation of effects to nearshore habitats include industrial structures that change the physical conditions that are important to nearshore biota, especially causeways that alter water temperature and salinity.

Effects of Oil on Marine Plankton and Benthic Organisms

The degree to which surface oil spills affect benthic communities depends on many factors, including the weather at the time of the spill, the biotic composition of the communities and their sensitivity to oil, and how deep they are (NRC 2003). Oils produced on the North Slope rise to the surface, and do not sink to the sea floor. Although surface slicks undergo some natural dispersion, the amount of oil reaching benthic organisms is less than one part per million (McAuliffe et al. 1981, Humphrey et al. 1987). Shallow benthic communities are vulnerable if oil strands on shorelines and is mobilized into the nearshore subtidal zone. Sometimes cleanup actually mobilizes oil to cause fairly high concentrations in nearshore subtidal areas. If there is a high load of suspended sediments in nearshore waters, oil can be adsorbed onto particles and be deposited in the nearshore subtidal area where it affects epibenthic organisms. Subsurface spills from pipelines released over extended periods could affect benthic communities close to the release.

Epibenthos and infauna are usually not abundant in very nearshore waters in the Beaufort Sea. Boulder patch communities are in deeper water and are only likely to be affected if a subsurface spill occurs in the immediate vicinity. If chemical dispersants are used, short-term exposure to fairly high concentrations of dispersed oil is possible. Short-term exposure to dispersed oil (from a single surface spill) is not likely to cause mortalities of the benthos. Mortalities could be caused from a prolonged surface leak repeatedly treated. Recovery of benthic epifauna is likely to be more rapid than is recovery of infauna. Recovery of boulder patch communities would probably take several years (Martin 1986).

Oil spills on or under spring ice would diminish primary production either as a result of toxic effects or because the oil would block light that passes though the ice sheet (Schell et al. 1982).

Some species of phytoplankton are more sensitive to oil than are others (NRC 2003). They can be affected by a surface oil slick or if dispersants are used and more oil enters the water column. The affected standing stock and primary production return to pre-spill conditions rapidly through natural transport of organisms from surrounding areas and rapid reproduction of these populations (Trudel 1986c). Fish larvae and eggs can be harmed by spilled oil, and oil can be ingested by higher trophic-level organisms with prey or as a result of prey contamination (NRC 2003). Thus, the effects of spills on phytoplankton communities generally are localized and short lived enough so that recovery occurs before effects accumulate.

Many zooplankton species, especially as larvae, are sensitive to oil. Studies of zooplankton have followed several oil spills, and localized, short-lived effects have been detected. There are seldom changes in biomass, however, because of high reproduction rates and rapid recrüitment from other areas (Trudel 1986d).

Effects on Biological Processes and Marine Communities

Studies of the Boulder Patch indicate that development of its kelp-community depends on four factors: There must be a hard substrate for attachment of algae and associated invertebrate fauna. There must be free (unfrozen) water under the winter ice canopy and protection from extensive ice-gouging and reworking at the bottom. There must be an erosional rather than depositional sedimentary environment (Dunton et al. 1982; Coastal Frontiers Corporation and LGL Ecological Research Associates, Inc. 1998). Those factors can exist in the vicinity of both natural and anthropogenic hard substrates.

As part of the Endicott environmental monitoring program, studies were conducted to measure long-term colonization of bare boulders placed at sites in the Stefansson Sound Boulder Patch. Colonization initially was slow, being negligible (Martin et al. 1988) or sparse after 3 years (Dunton et al. 1982). Five to six years were required before full colonization was achieved (Martin and Gallaway 1994). The slow appearance of colonizing organisms and the presence of uncommon species led Martin and Gallaway (1994) to suggest that Boulder Patch species disperse as relatively long-lived, slow-growing larvae. Species that fail to colonize could have a nonmotile dispersal stage or otherwise be limited in ability to disperse.

After 2 years in Stefansson Sound at drill island BF-37 red algae, particularly *Phyllophora truncata* and *Phycodrys rubens*, and one animal, a small hydroid had colonized gravel-filled bags (Toimil and Dunton 1983). No organisms were observed on the loose gravel at the base of BF-37. During inspections in 1994 and 1996 of gravel-filled bags and concrete mats placed as protective armor on Tern and Northstar exploratory drill islands, divers reported algae, worms, and soft coral (Craig Leidersdorf, Coastal Frontiers Corporation, personal communication cited in Wilson 2001). A 1998 survey reported algae about 2 m (6.5 ft) long, consisting of two distinct blades, probably representing 2 years growth, attached to coarse gravel (3-5 cm [1.2-2 in.]) lying near the toe at 6 m (20 ft) on Tern Island's western slope (C. Leidersdorf, Coastal Frontiers Corporation, personal communication cited in Wilson 2001). In the Stefansson Sound area, algae of this size likely would have been kelp, and those with distinct blades likely would have been *Laminaria*. Leidersdorf believed the plants colonized the gravel at the base of the island (Wilson 2001).

Laminaria solidungula and *L. saccharina* attached to coarse gravel have been collected along the eastern shore of the Endicott causeway after heavy easterly storms. Those plants with attached gravel were presumably moved westward along the bottom by surge and wave action created by storm winds and deposited along the causeway shoreline (Busdosh et al. 1985). It is possible that the kelp at the base of Tern Island were moved along the seabed by westerly storm conditions and deposited there.

Findings

- Other than those caused by permitted discharges and physical alterations or addition of structures, there have been few measurable effects on marine invertebrate communities from oil exploration and production operations on the North Slope.
- Hard substrates added to the marine environment in the form of causeways and artificial islands have been colonized slowly by benthic invertebrates.
- The Boulder Patch community has not been affected by oil operations.
- Monitoring is frequently required as a condition of discharge permits to ensure that discharges do not exceed water quality standards, are not toxic to marine organisms, and do not degrade water quality or pose a threat to human health. Most of the records of the monitoring programs are retained by the principal permitting agency, the U.S. Environmental Protection Agency, and are not readily available. Records also are kept by individual operators, but they are not summarized, and few annual reports are available.
- Oil operations have not had measurable population effects on epibenthic invertebrates, the sessile invertebrates of the Boulder Patch communities. The epontic communities under the ice have not been specifically studied, but it is unlikely that operations have affected them.
- Hard substrates added to the environment in the form of causeways and artificial islands have been slowly colonized by benthic invertebrates such as those found in the Boulder Patch.
- The committee found no data showing that discharges to the Beaufort Sea have had effects on biota. The trend is toward using disposal wells instead of discharging wastes directly to the ocean.

9

Effects on the Human Environment

> There is no turning back. We were introduced to the cash economy and now we can't do without it. How do we balance these? I don't know. We are learning it as we go. I don't know where is the middle place and I don't know what the future holds.
>
> Bernice Keigelak

> The land can tell us everything we want to know. The only problem is that it doesn't have a voice. But the spirit of the land is always there—talking to us. We must listen.
>
> Arctic Elder

Some effects on the human environment of oil and gas activities are analogous to effects on physical and biotic environments in that they are related in space and time to physical changes in the environment. But others differ in major ways because an effect on humans can occur without a physical change in the environment. Information—the announcement of a leasing decision, or knowledge about an event that occurred far away, for example—can profoundly affect people individually and collectively. These effects can occur before any local biotic or physical changes. Similarly, effects on people can occur by changing people's perception of risk or reward, and hence their behavior. Also, people can adapt faster and to a greater degree than many other organisms. As result of those differences, social and economic assessments on Alaska's North Slope must include an analysis of prior and distant effects. There is no analogy between the analysis of those effects and the analysis of any physical or biotic effect.

In addition, the harvesting of the wildlife resources that live or migrate through the region is of major cultural, nutritional, and economic value to North Slope residents. Although peoples in other rural areas traditionally hunt and fish for local wildlife, those activities are generally a supplement to other forms of subsistence activities such as gardening and timber harvest (Field and Burch 1991). There is no agriculture or forestry on the North Slope, so the Native cultural heritage there is based to a much greater degree on subsistence hunting and fishing than are subsistence cultures elsewhere.

Energy-resource development on Alaska's North Slope differs from the boomtown experience in the continental United States (Kruse et al. 1983). The isolation of rural communities on the North Slope, particularly because of their lack of connection to a highway network, meant they did not become staging areas for development. Instead, virtually independent infrastructures developed, centered on the terminus of the haul road that was built to support the Trans-Alaska Pipeline. The people hired to support the industrial development of the North Slope were not local or permanent, and in that they are similar to the populations that support offshore petroleum development elsewhere (Gramling 1989, 1996).

Because of these differences, the two research traditions that have guided much social and economic impact assessment are not entirely satisfactory. The first research approach flows from the National Environmental Policy Act (NEPA) of 1969, which requires that federal or federally funded agencies assess and mitigate the environmental effects of their actions.

The NEPA led to the birth of a variety of assessment techniques, summarized by Burdge (1994) and condensed into guidelines by the Interorganizational Committee on Guidelines and Principles for Social Impact Assessment (1994). The focus is to predict and evaluate social and economic effects *before* activities occur. It is necessary to describe baseline conditions (how the basic social and economic environment functions beforehand), identify the full range of probable social effects based on discussions with the affected parties, and project responses to the most likely effects. The approach identifies alternatives to the action proposed, and it establishes procedures for monitoring and mitigation.

The second tradition, which assesses the effects of development activities *after* it happens, has a long history, particularly in rural sociology (Field and Birch 1988; see Landis 1938). The focus sharpened in the early 1970s with research on the effects of the construction of coal-fired power plants in the rural western United States. The driving force of this "boomtown" model is population growth, which leads to a host of associated, frequently undesirable, societal effects. They include overcrowding; degradation of various municipal services, with a subsequent loss of informal control of deviance and community support of its disadvantaged members (Freudenburg 1986); and increases in substance abuse, divorce, homicide, and suicide (Albrecht 1978, Bates 1978, Cortese and Jones 1977, Gilmore 1976, Gramling and Brabant 1986).

To allow assessment of social and economic consequences related to oil and gas development on the North Slope, the committee used the typology developed by Gramling and Freudenburg (1992a, Freudenburg and Gramling 1992) in its analyses. In this typology, effects are separated into opportunity and threat effects, which can occur before any physical or biotic change; developmental effects, which occur during and soon after development activities occur; and adaptation and post-developmental effects, which generally occur after development is complete. Because developmental effects—those attributable to oil and gas exploration, development, and production—have been far greater on the North Slope than opportunity and threat or adaptation and post-developmental effects, they are discussed in the most detail.

OPPORTUNITY AND THREAT

In the human environment, real, measurable effects—*opportunity and threat effects*—begin with changes in social conditions and so can start with a rumor or announcement about a proposed activity (Krannich and Albrecht 1995). They result from the efforts of interested parties to define, and to respond to, the anticipated effects of development, either as an opportunity (for those who see the effects as positive) or as a threat (for those who see them as negative). Many effects on the human environment of the North Slope began with the announcement in 1968 of the discovery of oil reserves in Prudhoe Bay, and they were accomplished facts—or well on the way to becoming so—even before Congress approved construction of the Trans Alaska Pipeline in 1973.

Two types of information have resulted in the accumulation of opportunity and threat effects for the residents of the North Slope Borough: information concerning the initial find and information concerning various development scenarios.

Discovery

In January 1968, Atlantic-Richfield (ARCO) and Humble (now Exxon/Mobil) announced that they had found significant quantities of oil and natural gas at Prudhoe Bay. In July, ARCO estimated the find as 9.6 billion barrels (Berry 1975). The announcement of the discovery, the largest in the western hemisphere, was a catalyst for changes that affected the human environment of the North Slope and that increasingly moved North Slope residents into the mainstream economy. With the discovery, North Slope lands and waters that were the traditional Inupiaq hunting and fishing grounds suddenly had new meaning and value to the industrialized world to the south.

Although the concept of a pipeline to move oil from the North Slope to Valdez dates back to at least 1946 (Thomas 1946), the 1968 discoveries led engineers from British Petroleum, Humble, and ARCO to undertake more extensive studies. In 1969, those companies announced plans for a 1300 km (800 mi) long pipeline, at an estimated cost of $900 million. New companies joined the venture: Mobil, Phillips, Union of California, Amerada-Hess, and Home Oil. On June 6, 1969, they applied to the U.S. Department of the Interior for permission to build the pipeline across public land in Alaska.

In addition to opposition by environmental and commercial fishery groups there were two key legal impediments to the pipeline: long-standing native claims to the land across which the pipeline would traverse and the then-new NEPA. The importance of the land rights issue encouraged the multinational oil companies to support settlement of Native claims. Once that support was forthcoming Congress acted fairly quickly to pass the Alaska Native Claims Settlement Act (ANCSA) in 1971, which can be seen as the first major social and economic effect of petroleum activities on the North Slope. The ANSCA fundamentally changed the relationship between North Slope Alaska Natives and the environment they had occupied for thousands of years. The effects of that change accumulate to the present.

Congress chose a corporate model to address the issue of common "ownership" of native lands. The ANCSA created 13 regional corporations, 12 in Alaska and 1 to represent Alaska Natives living outside the state. Alaska Natives who enrolled were made shareholders. Approximately 200 village corporations also were created. Alaska Natives who enrolled in their village corporations received shares of that corporation. In general, Alaska Natives were allowed to enroll either in the region and village where they grew up and which they considered home, or in the region where they were living at the time the act was passed.

The act also provided for the distribution of $962 million in compensation to the regional and village corporations, essentially on a per capita basis. Of the funds, $462 million came from the federal government and $500 million came from state royalties on petroleum over a period of 11 years. Thus, approximately half of the original funds to establish the regional and village corporations did not come directly from North Slope petroleum activities.

One ANCSA provision requires that regional corporations share 70% of their resource revenues (those derived from timber or subsurface mineral rights acquired as a result of the ANCSA) with the other regional corporations. However, the Arctic Slope Regional Corporation (ASRC) would not be required to share resource revenues from its subsurface inholdings in the Arctic National Wildlife Refuge, because those lands were obtained in a land exchange (GAO 1989). This provision was designed to ensure that resource-rich corporations shared with those that were resource-poor simply by accident of location. This provision has had major and continuing effects.

Finally, under the ANCSA, 18 million ha (44 million acres) of land was conveyed to the regional and village corporations. Of that, 9 million ha (22 million acres) of surface estate went to village corporations, using a population-based formula. This land was generally located around villages and consisted of prime subsistence areas. The subsurface rights to this land, some 6.5 million ha (16 million acres), went to the regional corporations. However, under ANCSA, regional corporation selections for subsurface lands could not be made within existing national wildlife refuges. About 810,000 ha (2 million acres) was conveyed for specific uses, such as cemeteries, historical sites, and villages with fewer than 25 people, and another 1.6 million ha (4 million acres) went to reserves where the villages took land instead of land and money. The ANCSA also specified that if the secretary of the interior wanted to set aside a pipeline transportation and utility corridor, neither the State of Alaska nor Alaska Native groups could select lands within it. The ANCSA has been both praised and criticized, but its role in bringing permanent and still accumulating change to the lives of Alaska Natives on the North Slope and elsewhere cannot be denied.

The second major legal impediment to the pipeline, the NEPA, led to a bitter fight in Congress, primarily over a proposed alternative route through Canada and alternate sources of energy for the nation. The fight over the Trans Alaska Pipeline concerned loss of wilderness, marine oil spills at Valdez, earthquakes, and other issues (Coates 1991). The battle was finally settled, not by discussion or the NEPA process, but by the October 1973 oil embargo staged by the Arab members of OPEC. Shortly after the embargo began, opposition to the pipeline in Congress declined: the Trans-Alaskan Pipeline Authorization Act was passed November 12, 1973; and signed by President Nixon on November 16. The act barred further review on the basis of the NEPA, and it restricted further legal action only to questions concerning the act's constitutionality (Gramling and Freudenburg 1992b).

A third impediment in 1970 through 1973 was a technical review process that indicated the pipeline, as designed (to be buried), was vulnerable to failure by thawing permafrost and to destruction by plausible earthquakes. It mandated redesign according to specific technical stipulations (DOI 1972). The redesign, in which about half the pipeline is elevated, was completed during those three years. The estimated project cost rose from the original $900 million to $8 billion.

The haul road was completed in September 1974, and pipeline construction took the next three years. (For a concise description of the pipeline and associated facilities, see Coates 1991.) Oil first reached the Valdez terminal on July 31, 1977.

On the North Slope, the initial discovery started a chain of effects. The Arctic Slope Regional Corporation (ASRC) was created to serve as the North Slope's regional corporation; it is one of the major players on the North Slope. The North Slope Borough (NSB) was incorporated July 2, 1972. The North Slope Borough almost would certainly not exist except for

North Slope petroleum, but if it did exist it would certainly not be the dominant social, economic, and political force that it is today.

The initial discovery at Prudhoe Bay, the subsequent enactment of the ANSCA, establishment of the ASRC and the village corporations, and the founding of the NSB have been the primary factors in the growth, concentration, and development of the communities and populations on the North Slope. Without petroleum development on the North Slope, those communities and populations, and the conditions under which they live would be vastly different. The initial announcement of the discovery at Prudhoe Bay resulted in the restructuring of the social, economic, and political life on the North Slope in a way that allowed large amounts (by North Slope standards) of capital to flow into the region. That capital resulted in major changes in North Slope communities.

Specific Development Scenarios

Information about two specific development scenarios has led to significant opportunity and threat effects: offshore development and development in the 1002 Area of the Arctic National Wildlife Refuge.

Offshore Development

The 1983 observation of Kruse and colleagues, that Native Alaskans' "fears that offshore development will inevitably harm subsistence resources are both intense and widespread and themselves constitute an impact of development," is still true. The committee was repeatedly told that this is *the* issue for the Inupiat.

The concerns fall into three categories, all involving the bowhead whale. The first is that the Inupiat do not believe anyone has demonstrated the ability to clean up oil spilled in a frozen sea or in broken ice. In fact, many have voiced the belief that large marine spills cannot be cleaned up in any situation, citing as evidence the *Exxon Valdez* spill and the failure of any large marine spill to be contained and cleaned up (see also ADEC 2000). The *Exxon Valdez* oil spill was a sensitizing event on the North Slope, as it was around the world, in reinforcing the perceived consequence of a large marine spill. Along the coast, the first concern is that a spill during the migration of the bowhead and will injure or kill significant numbers of whales. The Inupiat believe this would be especially critical during the spring migration when both spilled oil and whales would be concentrated in leads (cracks in the ice cover).

The second concern is that a spill would cause the International Whaling Commission to judge the bowhead to be under greater threat than is currently perceived, causing that group to curtail or reduce quotas for the striking of whales. The final concern is that the noise associated with offshore exploration and production would alter the migration routes of the bowhead. This concern is based both on observations by Inupiat hunters and on recent scientific data that bowheads will avoid seismic activity, moving as much as 20-30 km (13-19 mi) away from their normal migration routes (Richardson 1997, 1998, 1999). When whales move farther from shore, the hunters must follow in their small boats to unpredictable seas, and tow killed animals farther, as well. Hunters are exposed to greater danger and the amount of the harvest is reduced because of spoilage.

It would be difficult to overstate the importance of bowhead hunting to the Inupiat. The subsistence harvest dates back several thousand years, but outside influences have brought about social changes, and so whale hunting has become a rallying point for the maintenance of Inupiaq cultural continuity in at least four important ways. First, the organization of whaling crews and the preparation for the hunt is a continuous activity that creates and reinforces social and cultural bonds. Second, the hunt itself is an intensive experience that involves crews camping out on the ice, near a lead, for up to a month. Third, the preparation and preservation of a successfully taken whale involves the entire community. Luton (1986) estimated that 70% of the entire population of Wainwright was directly involved after the successful taking of a bowhead. Finally, sharing the whale is an integral part of Inupiaq culture that reinforces cultural continuity and that goes beyond social action to the way Inupiat are intertwined with the world. For the Inupiat, the only way humans can take an animal as powerful as a bowhead whale is if the whale gives itself to the hunters. Whales will do this only if they are treated with respect. Sharing the whale is one way of showing respect, as are activities such as cleaning the ice cellar, the final resting place of the whale. Whales are shared in three ways. First, whales are shared by whaling crews according to a community formula (Luton 1986). Second, as with other subsistence commodities, once a crew member has received his share, various portions of the whale are shared with relatives, friends, and elderly members of the community and others who cannot participate directly in the hunt. Finally, a large part of the successful captain's share of the whale goes to the Nalukataq, a festival and important community gathering that includes a blanket toss, dancing, and the sharing of food.

Each successful captain holds a Nalukataq (usually the last two weeks in June), and friends, relatives, and former community members travel to the community to visit and catch up on what has happened over the past year. No other shared pursuit involves as many members of the community, for as much time, and as intensively as the activities that surround hunting the bowhead. In Barrow, hundreds of thousands of person-hours are spent in those activities (Harcharek, unpublished material, 2001). The same is true in other North Slope whaling communities.

Finally, the size of bowheads makes them an extremely important food source. It is doubtful that any of the North Slope communities could survive in their present form without the harvest. Of the 74% of NSB households that responded to a 1998 survey, 68.7% of Inupiaq households and 36.4% of non-Inupiaq households reported that at least one-half of their annual food came from subsistence activities.

Hunting the bowhead has been the Inupiaq cultural anchor as change has come to the North Slope. The ongoing, accumulating effects posed by offshore development, in the form of perceived threats, would be diminished only by clear evidence that the technology exists to mitigate large oil spills in broken ice. There is no evidence to date that such cleanups are possible. Current mechanical means of collecting spilled oil are not likely to be successful in the Beaufort and Chukchi seas (ADEC 2000). Alternative methods, such as in-situ burning and chemical dispersion, still must be developed for use in ice-filled waters, incorporated into response plans and practiced, and approved by regulatory agencies.

Engaging in subsistence activities is not simply a matter of choice. Isolation from major transportation routes and the area's inability to produce agricultural products mean that the prices of goods and the cost of transporting them to the North Slope are considerably higher than in the rest of Alaska or in the continental United States. In 1998, the cost of a "typical market basket" in Anchorage was $122.19; in Barrow it was $218.03 (NSB 1999); it is substantially higher in outlying North Slope villages. Costs for vehicles, construction materials, fuel, appliances, and tools are similarly inflated in the North Slope. This does not mean that Barrow residents spend 178% of what residents in Anchorage spend; indeed they cannot. Because North Slope residents do not have greater per capita incomes than some of their counterparts in Alaska or in the United States in general, they must have a lower standard of living, rely to a greater extent on subsistence harvest, or both. Accordingly, examination of any potential effects on subsistence resources is critical to the assessment of the accumulation of effects of energy development on the human environment.

Development in the 1002 Area

The Gwich'in Indians are a traditionally nomadic people who follow the migration of the Porcupine Caribou Herd (Mishler 1995, Time-Life Books 1998). For thousands of years, their ancestors have relied on caribou to meet their nutritional, cultural, and spiritual needs (Gwich'in Niintsyaa 1988). The Gwich'in Nation consists of 15 villages in northeastern Alaska and northwestern Canada (Arctic Village, Christian, Venetie, Beaver, Birch Creek, Fort Yukon, Stevens Village, Circle, Eagle Village, Chalkyitsik, Old Crow, Fort McPherson, Arctic Red River, Aklavik, and Inuvik), all of which are outside the North Slope. However, the coastal plain of the North Slope, primarily the 1002 Area of the Arctic National Wildlife Refuge, is the traditional calving ground for the Porcupine Caribou Herd. The Gwich'in believe that oil- and gas-related activities there would affect the reproductive potential and migration patterns of the Porcupine Caribou Herd and as a result threaten their way of life. As with the Inupiaq concerns about offshore development, the beliefs are intense and widespread and themselves constitute a continuing effect that is exacerbated by the past and current political debate over development in the Arctic National Wildlife Refuge.

As an indication of the strength of their concerns, in 1988, in response to initial attempts to open the refuge, the Gwich'in Nation met in Arctic Village to draft a resolution petitioning the Congress and president to preserve the right of the Gwich'in people to their life-style by prohibiting development in the calving ground of the Porcupine Caribou Herd and to designate the 1002 Area of the Arctic National Wildlife Refuge as wilderness.

The residents of Kaktovik, who live on Barter Island at the northern edge of the Arctic National Wildlife Refuge coastal plain, are generally in favor of environmentally sensitive development there, which could bring significant economic resources to them.

EFFECTS OF DEVELOPMENT

Most research on effects on the human environment has focused on development effects—those associated with the actual development, construction, and operation of a project or with the onset of a particular activity or process. Development activities also can alter physical systems in ways that affect humans, and they can alter cultural, social, political, economic, and psychological systems. Development effects have been studied the most and are the best understood of all socioeconomic consequences. A variety of effects can be observed on the North Slope, including those attributable to noise and disturbance, availability of money, and alterations to the physical environment, with indirect effects on people.

Noise, Bowhead Whales, and Subsistence Hunting

Inupiaq hunters in the coastal villages first expressed their concerns about seismic noise affecting fall-migrating bowheads in the 1980s (Ahmaogak 1985, 1986, 1989). The hunters' contention was that seismic disturbances were forcing the bowhead off shore, making access to the whales more difficult and time making the whales more wary and therefore more difficult to hunt.

However, early scientific studies concluded that the bowheads did not react strongly to an approaching seismic vessel until it was within 7.5 km (4 mi) (Ljungblad et al. 1985, 1986, 1988). Native hunters strongly disagreed with this assessment, and eventually two apparent problems with its methods were identified. First, the whales were approached by the boat, rather than the whales approaching the boat. Thus, what was measured was how close a seismic vessel needed to approach to force whales to move out of an area they were already in, rather than to what extent migrating whales would alter their paths to avoid a seismic vessel. Second, in three of the four experimental situations in the study there was already another seismic boat "booming" in the distance before the test boat began. This compromised the controls. Those problems led scientists to conduct more carefully controlled studies in the late 1990s. Data from three years showed that nearly all fall-migrating bowheads stayed 20 km (12 mi) away from an operating seismic vessel, a finding that supported native observations (Richardson 1997, 1998, 1999). In addition to avoiding active seismic vessels, whales change their rate of calling as they approach seismic sources. Data from seismic monitoring in 1996 and 1997 show that call rates changed at least 45 km (27 mi) from an active seismic vessel (Richardson 1998), probably indicating detection of seismic activity. (Details of the effects of noise on whales and other marine mammals are in Chapter 8.)

In recent years, the Alaska Eskimo Whaling Commission (AEWC) and seismic-exploration operators have reached an agreement that reduces the effects of seismic noise. The "oil-whaler agreement" restricts seismic vessel operations to the west of the Nuiqsut and Kaktovik hunting areas until the subsistence hunt has been completed. The agreement must be renegotiated annually because the areas of seismic operation vary each year. The National Marine Fisheries Service (NMFS) established the program and continues to require operators to cooperate with the AEWC. Although the agreement is helpful, substantial expense of time and resources is required for AEWC negotiations each year in full consultation with its members in the affected villages.

Petroleum activities on the North Slope have affected, and have the potential to affect, subsistence activities in several ways. Direct effects have been documented in three areas. First, traditional hunting areas within active oil fields are now closed to hunting. Second, offshore activity alters bowhead migration routes. Third, as noted in Chapter 8, calving caribou tend to avoid intensive oilfield activity, shifting to less disturbed areas. As activities expand on the North Slope those effects could expand as well.

In addition to the effects noted above, Alaska Native residents told the committee that there are subtle changes in species harvested by subsistence hunters, who have identified changes in the color, texture, and taste of the flesh and skin of several species.

Alterations to the Land

Alterations to the North Slope physical environment have had aesthetic, cultural, and spiritual effects on human populations. They come primarily from construction of roads, pipelines, buildings, and powerlines, and from offroad travel.

Structures and Roads

Before the completion of the haul road in September 1974, the only regular, mechanized access to the North Slope was by air, or by water during the late summer and early fall. Increases in settlement, agriculture, and forestry generally accompany road building in temperate and tropical areas, but for the North Slope the most relevant effect is the increased hunting pressure that accompanies roads (Box 9-1). Currently, roads of the industrial development stretching from Kuparuk to Endicott are closed to public traffic, but should any of them be opened to public use, effects would increase. The Alaska Department of Transportation is considering a new all-season road to connect the National Petroleum Reserve-Alaska with the Dalton Highway (Petroleum News Alaska 2002).

Box 9-1 Recreational Fishing and Hunting

Fish, mammals, and birds on the North Slope are taken by subsistence, commercial, and recreational users. Here we consider the effects of recreational fishing and hunting.

Fishing

Recreational fishing is mostly for Dolly Varden char and arctic grayling, although lake trout, burbot, pink salmon, chum salmon, and whitefish are also taken (as reported in the Alaska Department of Fish and Game [ADF&G] annual catch surveys, such as that by Howe and colleagues [2001]). From 1977 to 1981, the annual fishing effort averaged 2,030 angler days (range: 1,422-2,601), but since then it has averaged more than 5,000 angler days (range: 2,541-8,344). Effort as measured by the number of angler-days increased after completion of the Dalton Highway but appeared to stabilize after 1981. Reported catch rates of Dolly Varden char and arctic grayling declined from peaks in the early and mid-1980s to about 1990 and have fluctuated with no significant trend since then. However, before 1990 only fish taken were reported. After 1990, the estimates also include fish caught and released, reflecting that increasingly common practice (Howe et al. 2001). Thus, it is possible, and perhaps likely, that the change in reporting has masked a decline in catch rates.

The catch-per-unit-effort (CPUE), a measure of how many fish are caught for a given fishing effort, has declined substantially since the mid-1980s. CPUE is related to fish abundance and to other factors, such as the fish learning to avoid capture, which substantially affects CPUE for catch-and-release fishing. It is difficult to accurately estimate the number of fish caught and released by recreational anglers. Catch-and-release fishing usually has little effect on the populations of targeted fishes (Policansky 2002), so it is difficult to evaluate how the effects of recreational fishing accumulate with other effects on the target populations.

Box 9-1 (continued)

Hunting

Records of recreational hunting kills in Game Management Unit 26 (the North Slope) start in 1977 for sheep and moose, in 1960 for brown bears, in 1981 for caribou, and in 1984 for wolves. The latest information available is for 2001: records for caribou were not available between 1983 and 1997. Because the Dalton Highway was completed in 1974, the records do not permit any evaluation of its effect on hunting other than for bears, but observation and anecdote indicate that hunting increased after the road was completed.

Recreational caribou hunting varies widely from one year to another. For example, in 2000, 979 animals were taken; only 74 were reported killed in 2001, although the information for that year appears incomplete. All other years for which there are records, more than 360 caribou were taken. The recorded take of sheep was around 200 in most years, with a few years recording slightly more than 300. The number of bears ranges from 1 in 1960 and 1962, to 51 in 1990, and 62 in 1991. No clear trend is apparent except that relatively few bears were taken before 1963 and more were taken in the early 1990s than at other times. In most years between 1979 and 1995, 100-200 moose were taken; 48 were taken in 1977 and 81 were taken in 1978. Since 1995, the annual take has declined markedly, ranging now from 5 to 17 animals per year. The annual take of wolves was a low of 2 in 1984 to a high of 91 in 1993, but other than an increase after 1987 and a peak in the early 1990s, no clear trend is apparent.

The available information makes it clear that hunting is a source of mortality for the target species that likely has increased as a result of the opening of the Dalton Highway. However, no obvious population effects have been documented, so the committee was unable to assess how the effects of recreational hunting accumulate with other effects on the target populations.

Access by Nuiqsut caribou hunters to oilfield complexes has been reduced because hunting is prohibited within some, but not all, such areas. Physical barriers to use of all-terrain vehicles, and snowmachines are posed by pipelines, and many hunters are reluctant to enter the oilfields for personal or aesthetic reasons. The committee heard repeatedly from North Slope Inupiat residents that the imposition of a huge industrial complex on the Arctic landscape was offensive to the people and an affront to the spirit of the land.

The roads and gravel pads are not likely to be removed because exploration and development leases do not generally require rehabilitation. Rather: "[A]t the option of the state, all improvements such as roads, pads, and wells must either be abandoned and the sites rehabilitated by the lessee *to the satisfaction of the state*, or be left intact and the lessee absolved of all further responsibility as to their maintenance, repair, and eventual abandonment and rehabilitation" (Alaska Division of Oil and Gas 2002, emphasis added). It was the State of Alaska, not the oil companies, that pushed for public access to the Dalton Highway. Thus, the extent of permissible access to the infrastructure associated with current and future petroleum production on the North Slope ultimately rests with the state government.

Off-Road Travel

The primary effects of off-road tundra travel are imprints on the land that persist for varying amounts of time. Off-road travel does physical damage to the land and vegetation, and the tracks laid down by various types of vehicles are aesthetically unpleasing. The recognition that imprints of human activity make a qualitative difference in a landscape can be seen in the wording of the Wilderness Act of 1964 (PL 88-577): "[A] wilderness, in contrast with those areas where man and his own works dominate the landscape, is hereby recognized as an area where the earth and its community of life are untrammeled by man..." As with most questions of aesthetics, different people—perhaps even entire cultures—are affected differently by seeing, or just knowing about, changes to the environment caused by human activity. That the landscape is altered, however, is undeniable.

Seismic exploration leaves an imprint on the landscape, particularly the more recent 3-D (three-dimensional) methods that require receptor lines to be much closer together than earlier methods. Of the activities associated with seismic surveys, the camp trains (pulled by D-7 Caterpillar bulldozers) appear to leave the most visible scars. It is not known how long the tracks left by seismic activity will remain on the tundra; however, some of the tracks left in the 1984-1985 seismic surveys in the Arctic National Wildlife Refuge are still visible.

Human-Health Effects

During the committee's four meetings in Alaska, residents offered individual perspectives on many subjects, and we heard testimony about both positive and negative effects from oil and gas development. Alaska Natives recognize that oil production in the region has given them money to spend on community facilities, schools, modern water and sewer systems, village clinics, child emergency shelters, and behavioral outpatient and residential programs that provide mental health care and counseling for substance abuse and domestic violence. North Slope residents reported that money has increased the quality and quantity of health care for elders, especially for those who need assisted-living services. Each individual receives a permanent fund dividend every year that is funded by investment of state money. Barrow residents already enjoy low-cost natural gas heating for their homes, and other communities are expected to receive it soon. Some residents believe that the access to the Internet increasingly will provide people with education without the cost of travel or absence from the village.

North Slope residents also reported that traditional subsistence hunting areas have been reduced, the behavior and migratory patterns of key subsistence species have changed, and that there is increased incidence of cancer and diabetes and disruption of traditional social systems. They also see vastly increased time, effort, and funding necessary to respond politically and administratively to the ever-multiplying number of projects proposed in their own back yards.

Alaska Natives told the committee that anxiety over increasing offshore and onshore oil and gas activity is widespread in North Slope communities. Hunters worry about not being able to provide for their families or about the added risk and expense of doing so if game is more difficult to find. Elders who can no longer provide for themselves worry about the challenges facing younger hunters who will go to great lengths to provide them with essential and traditional foods. Families worry about the safety of hunters who must travel farther and more often if game is not easily accessible. Many adult residents already lead dual lives as wage earners and subsistence providers for their families. They also are faced with the need to attend industry-related meetings and hearings, and review documents, because they believe that decisions will be made that can significantly affect their daily lives and those of generations to come. They worry about contamination of the food they consume and know that their health will suffer if they are unable to eat as their ancestors did.

In addition to stress contributing to adverse health effects, oil development has increased the smog and haze near some villages, which residents believe is causing an increase in asthma. The stress of integrating a new way of life with generations of traditional teachings has increased alcoholism, drug abuse, and child abuse. Higher consumption of nonsubsistence food, such as shortening, lard, butter, and bacon, and reduced consumption of traditional foods, such as fish and marine mammal products, have increased the incidence of diabetes (Ebbesson et al. 1999).

The NSB bears the costs of those social stresses. Villages now provide substance abuse treatment, counseling, public assistance, crisis lines and shelters, and other social service programs. The borough provides the search and rescue services that respond when hunters put themselves at risk in the pursuit of less accessible game. The revenue from oil development has funded a police force, which must respond to the situations that arise when people and their communities are subjected to long-term and persistent stress. The borough supports biologists, planners, and other specialists who review and offer recommendations on the volume of lease sale, exploration, and development project documents that are produced each year. It must also cover the ever-increasing expense of travel to Fairbanks, Anchorage, and Juneau, Alaska; Seattle, Washington and Washington, D.C., where agencies with authority over oil and gas leasing, exploration, and development, and the subsistence resources they depend on, conduct most of their work and make most of their decisions. Although many public services would not have been possible without the revenue from oil development, many of those public services would not have been necessary if oil had not been found and extracted from the North Slope.

Wilderness and Wildlands

The only legally designated wilderness areas under study by the committee is a portion of the 3.2 million hectare (8 million acre) Mollie Beattie Wilderness that lies north of the Brooks Range within the Arctic National Wildlife Refuge and a small segment of Gates of the Arctic National Park north of Chandler Lake (Box 9-2) (NWPS 2002). The Wilderness Act expressly prohibits the construction of roads and structures and the use of motor vehicles, motorized equipment, and motorboats, or aircraft and other mechanical transport, in formally designated wilderness [Sec. 4(c)]. However, the Alaska National Interest Lands Conservation Act (ANILCA) of 1980 subsequently authorized the use of motorized boats and snowmobiles, subsistence hunting and fishing, the construction of temporary structures, and the landing of airplanes and other activities in Alaska wilderness areas.[1]

In addition to formally designated wilderness, more than 300,000 ha (750,000 acres) of federal land in the 5.2 million ha (12.8 million acre) area between the Arctic National Wildlife Refuge and the National Petroleum Reserve-Alaska has been collectively managed by the Bureau of Land Management (BLM) as a wilderness study area (R. Delaney, BLM, personal

[1] Sections 811,1110, 1316 of ANILCA and 50 CFR Sec. 36.12. See 66 F.R. 3716 et seq. for a discussion of ANILCA exceptions to wilderness study area (WSA) prohibitions.

communication, 5/17/01 and 1/30/02).[2] BLM is required to maintain the wilderness character of this area. Although the amount of formally designated wilderness on the North Slope is small, a substantial portion of the slope outside the oil fields retains the characteristics of wildlands and is de facto wilderness (TAPS Reapplication EIS).

Box 9-2 The Arctic National Wildlife Refuge

Wilderness was perhaps the most prominent of the values the Arctic National Wildlife Refuge was established to protect. Refuge founders Olaus and Margaret Murie, George Collins, Lowell Sumner, and U.S. Supreme Court Justice William O. Douglas focused their work to establish the refuge on the theme of "America's Last Great Wilderness," and their writings are replete with references to the wildland values of the area and to its status as one of the last large, wild systems remaining in the United States (FWS no date). Additional purposes of the refuge were to preserve unique wildlife and recreational values, including the Porcupine caribou herd, polar bears, grizzly bears, and other mammals and birds, and Arctic char and grayling; to fulfill international fish and wildlife treaty obligations, to provide for continued subsistence use by local residents, and to ensure water quality and quantity (FWS no date).

In 1960, the 3.6 million ha (9 million acre) Arctic National Wildlife Range was established by the secretary of the interior. In 1980, the ANILCA more than doubled the size of the range and renamed it the Arctic National Wildlife Refuge. Some 3.2 million ha (8 million acres)—or about 40% of the refuge—is legally designated wilderness. The 1002 Area is not part of the designated wilderness. The U.S. Fish and Wildlife Service seeks to preserve the same level of naturalness on both designated and de facto wilderness within the refuge (Kaye 2000).

Wilderness

The term "wilderness" carries many connotations, depending in part on the cultural and historical perspectives of the beholder. The definition provided by the Wilderness Act of 1964 is viewed with profound skepticism and resentment by many Alaska Natives, who have lived for generations in "wilderness" areas on Alaska's North Slope:

> None of this country is wilderness, nor has it ever been. It has been continuously used and occupied by us and by our ancestors for millennia. Since wilderness is defined as a place without people, we are deeply insulted by those who proclaim any of this country wilderness, as if we were not considered to be real people (From *In This Place* [Anonymous, unpublished, 2001]).

Although reconciling the various views is a task well beyond the committee's charge, some commonalities are worth noting. Some ideas embodied in the legislative vision of wilderness are also seen by Alaska Natives of the North Slope as essential elements of their history and culture:

---

[2] Due to transfers of some of this land to the state and native corporations, this number is now less than 750,000. BLM does not have an accurate accounting of the current area managed as WSA in this area.

> We told these [visitors] we liked the mountains and we liked the sea. We liked to spend as much time in these places as we could, the frozen sea, the snowy mountains, the summer sea, this gorgeous, ever changing, breath-taking country which is our homeland. Nowhere else is all of this possible, a sea full of great whales and seals and fish and polar bear and foxes and birds of every kind, from nearly every land, with mountains just nearby full of white sheep and wolves and wolverine and with great plains in between the mountains and the sea with muskoxen and caribou and river and lake fish and many more birds and a thousand other things, all intermingled with the spirits and memories and stories and legends and graves and old houses of our people. This is the perfect place, the perfect place for us, which is why God probably put us here, these few of us, and made us tough enough to stay (From *In This Place* [Anonymous, unpublished, 2001]).

The nature and intensity of human use, along with the persistence of evidence of such use, determine the extent to which an area retains its wild, "untrammeled" character. Land use by indigenous peoples on the North Slope has been for the most part nonintensive, leaving few traces on the landscape outside of established villages. In contrast, oil development has altered the landscape in ways that will persist long after oil and gas extraction ceases. Testimony provided to the committee in various communities on the North Slope repeatedly cited "scars on the land" that result from industrial development and that have altered both the physical and the spiritual elements of the landscape, and thus the very basis of Alaska Native culture on the North Slope. Many Alaska Natives argued, however, that a wilderness designation can unfairly exclude them from their own ancestral land. However, the Gwich'in people support wilderness designation of the 1002 Area as the appropriate legal tool to protect their subsistence way of life.

Although acknowledging the existence of divergent views, the committee evaluated the effects of oil development on wilderness as the term is defined in the Wilderness Act. To avoid confusion, we use the word "wildlands" rather than wilderness except when discussing legally designated wilderness. A typology of wildland values is presented in Figure 9-1.

Effects of Development on Wildlands

Before oil development began in 1968, the area north of the Yukon River, including the North Slope, was considered the largest intact wildland area in the United States (DOI 1972, FWS 1987). Since that time, a large segment of this region has been transformed. The perimeter of the oil fields now extends over some 2,600 km^2 (1,000 mi^2) of the North Slope, an area roughly equivalent to the land area of Rhode Island. The oil fields constitute one of the world's largest industrial complexes, and they have substantially affected many of the wildland qualities of the region. The associated roads, pads, pipelines, seismic vehicle tracks, transmission lines, air, ground and vessel traffic, drilling activities, landfills, housing, processing facilities, and other industrial infrastructure have reduced opportunities for solitude; displaced animals; altered ecological processes; compromised scenic values; and resulted in noise and air emissions. Because the landscape is open, the changed nature of the landscape—the roads, pads, pipelines, other structures, alterations of the tundra from seismic activities—is visible at a distance, particularly from the air. Similarly, changes in noise and air quality are perceptible far beyond points of emission. All of these effects have resulted in the erosion of wildland values over an area that is far larger than the area of direct effects.

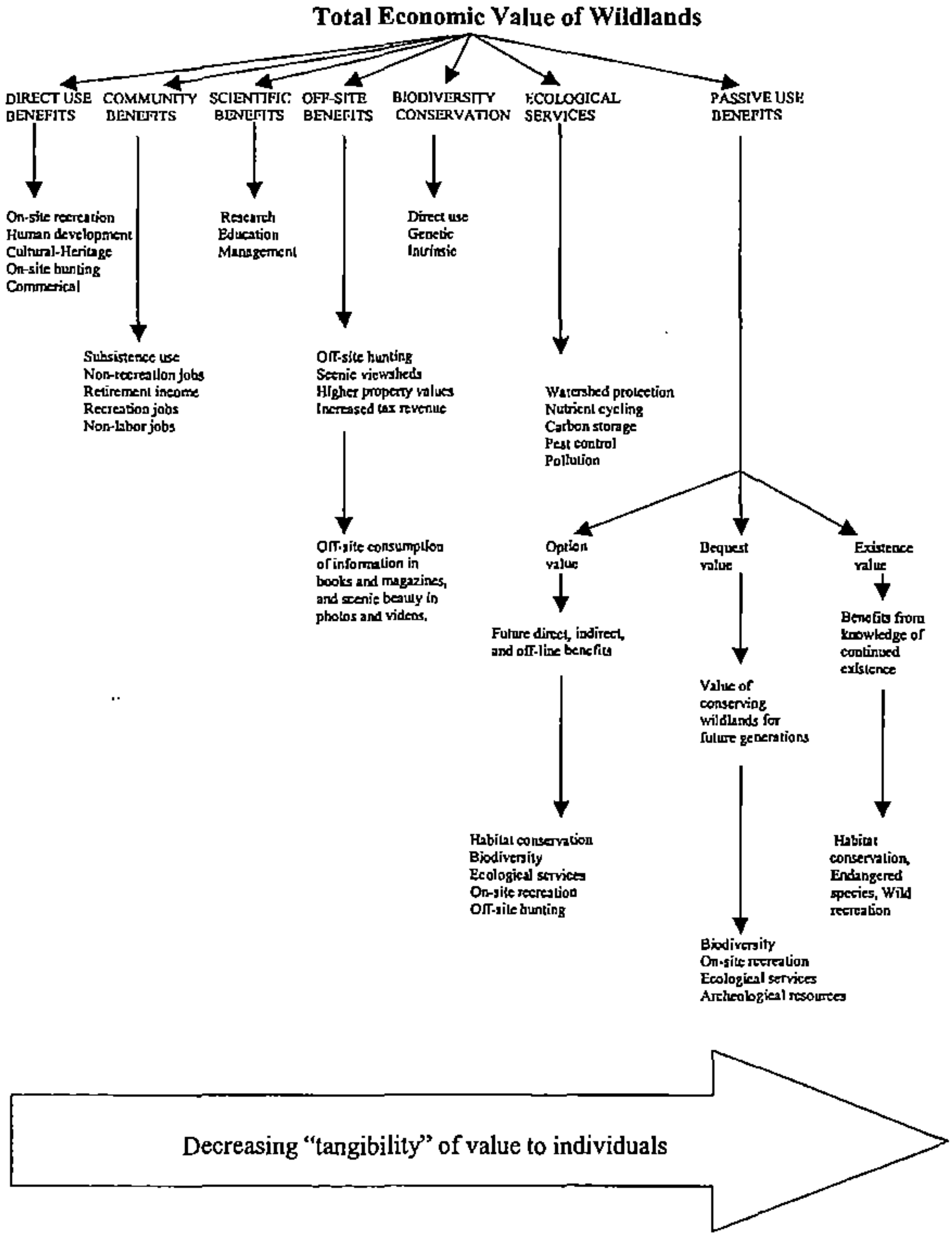


Figure 9-1. Total Economic Value of Wildlands. Source: Morton 1999.

Most analyses of effects on the wilderness and wildlands of the North Slope have been conducted in the context of environmental impact statements. And the analyses generally are cursory and often out of date. None has used new techniques for measuring wilderness values; none has attempted to coordinate wilderness planning or assessment among different jurisdictions.

The National Petroleum Reserve-Alaska Production Act of 1976, for example, required BLM to examine all resource values, including wilderness values, in the National Petroleum Reserve-Alaska. This analysis (known as the 105(c) study) was completed in 1978, almost a quarter of a century ago. It is the only comprehensive wilderness evaluation that has been done for the entire National Petroleum Reserve-Alaska. In connection with the 1996 decision to open up the northeast portion of the reserve to leasing, BLM prepared an integrated activity plan/environmental impact statement (IAP/EIS). At the time, BLM was barred from recommending wilderness designation (which would require an act of Congress) for any portion of the area under consideration under a directive issued in 1981 by then Interior Secretary James Watt. As a result, although the IAP/EIS for the northeast lease sale area contains scattered references to the wildland values of the area (principally focused on recreation), there is little meaningful analysis of the consequences of development for the range of wildland values.

Economic Benefits

The cash economy of the North Slope Borough largely would not exist without oil and gas production. To supplement their subsistence activities, some residents would have earned income from U.S. government transfers such as social security, medical and veterans' payments, or Bureau of Indian Affairs payments. Sport hunting, fishing and other recreational activities would have generated some income. And although the ASRC has generated some earnings recently, without North Slope oil that corporation would not exist.

Table 9-2 is a summary of total personal income data for residents in the NSB. After oil production began in the late 1970s there was a dramatic increase of total personal income. The NSB was established in 1972. Per capita income in 1999 was about $27,000. For comparison, per-capita income in Arctic Village, not part of the NSB, was $10,761 in 2000.

Table 9-2 Total Aggregate Personal Income for the Alaskan North Slope, 1970-1999

	Year	Total Personal Income (millions $)
Barrow-North Slope Division	1970	12.4
	1975	42.4
North Slope Borough	1980	82.1
	1985	133.6
	1990	145.6
	1995	200.6
	1999	205.8

Source: BEA 2002

Personal income is not necessarily the best measure of effects, especially over the long term. Another, longer-term accumulating effect is the progressive exhaustion of oil and gas resources, because current and past cash income has been purchased at the cost of denying income to others in the future.

An informative way to illuminate the accumulated beneficial aspect of oil and gas development is to measure net assets on the North Slope. Assets are a measure of the private and public wealth of an economy that, by their nature, represent the accumulation of value over time. In contrast, income represents value earned for a relatively brief period, such as a year.

Table 9-3 summarizes the private and public assets on the North Slope as of 2000. More than 90% of the private property value on the North Slope, including oil deposits, is directly attributable to the oil sector. Most private property is taxed, and that revenue supports public services in the borough. A region that has a substantial tax base, such as private petroleum assets, can collect corporate taxes to provide generous social services or to reduce its private citizens' tax liabilities.

Over time, the NSB has used its income to create net public assets that stood at $1.8 billion in 2000. The public and private net assets that year amounted to $13.4 billion—more than $1.77 million per capita. It is hard to compare such figures with those for counties or for other small towns, because public assets generally are not recorded. Instead, a comparison is made with private assets. A sample of a dozen small towns in Washington state (population 5,000-10,000) reveals a private per capita taxable asset value owned by individuals, corporations, and other taxable sources averaging about $74,000; on the North Slope it is about $1.53 million.

Table 9-3 Net Assets: North Slope Borough and Private Assets, 2000

	Assets/Liabilities ($ millions)	
Private Assets		11,607
Petroleum	10,528	
Other Private	334	
Exemptions	745[a]	
North Slope Borough Assets		2,937
Cash and investments	903	
Profits	713	
Physical improvement	372	
Other	949	
Borough liabilities[b]		1,152
Net Assets		13,392

[a]Tax exempt value for 2001

[b]Personal communication, Dennis Packer, Office of the Mayor, North Slope Borough, February 27, 2002.

Source: Comprehensive Annual financial Report of the North Slope Borough, Alaska, 2000. pp. 29, 31, 33, 104-105, 108.

North Slope Borough

The North Slope Borough is the dominant economic force in North Slope communities. Petroleum activities have been and continue to be the primary source of income on the North

Slope. In addition to property tax revenue from petroleum installations, income flows into NSB communities from royalties paid to the State of Alaska, which are returned to the NSB; through direct oil-field employment of NSB residents; and through the activities of the regional and village corporations.

The property taxes underpin the current NSB economy. In the 1999-2000 fiscal year, revenues for the NSB were $240,105,567, of which $201,223,579 (83.8%) came from property taxes. Of that amount, $192,524,702 (95.4%) was paid by five petroleum companies. Fifty-two percent of all jobs reported in the NSB 1998 survey are funded by the borough. Thus, petroleum activities have had massive developmental effects on the economy of the NSB and on the lives of its residents (Table 9-4).

Table 9-4 North Slope Borough Revenue, 1991-2000 ($ Thousands)

Fiscal Year	General Property	General Sales/ Economic Impact Assistance	Inter-government	Charge for Services	Miscellaneous	Total
1991	221,630	4,408	36,796	7,786	45,345	315,965
1993	235,928	5,009	30,209	8,663	51,337	331,146
1995	227,292	5,000	32,664	10,497	37,714	313,167
1997	223,923	4,900	32,240	11,643	43,018	315,724
1999	211,512	4,700	33,900	13,935	27,770	291,817
2000	201,224	4,600	37,088	9,493	30,213	282,618

Arctic Slope Regional Corporation

The Arctic Slope Regional Corporation currently receives annual revenues of approximately $1 billion. Throughout its existence, it has distributed approximately $123 million in dividends to its shareholders, and it currently employs more than 500 of those shareholders (ASRC 2001). In 2000, the ASRC distributed $8,841,000 through shareholder dividends, through distributions from its permanent fund, and through its Elders' Settlement Trust investment fund program. The ASRC subsidiaries were heavily involved in the construction and drilling of the Alpine field, which recently came on line, and the ASRC owns, with the state, the subsurface mineral rights to the Alpine field. The ASRC and the village corporations have been and continue to be dominant economic forces on the North Slope. ASRC subsidiaries employ the overwhelming majority of North Slope residents who work in the oil and gas sector on the North Slope (Alaska Petroleum Contractors Inc. and Houston Contracting Co-Ak Lt. employed 50 of the 64 employees noted by Alaska Department of Labor and Workforce Development in 2001). The ASRC owns the mineral rights to approximately 2 million ha (5 million acres) of land on the North Slope, much of which has proven reserves of, or holds promise for, oil, gas, coal, and base metal sulfides. The ASRC and its subsidiaries constituted the largest local property tax payers on the North Slope in fiscal year 1999-2000 (NSB 2000).

State Royalties Returned

Another useful economic measure of the accumulation of effects is the Alaska Permanent Fund. Royalties from oil sales, which have accumulated in this fund, amounted to more than $28 billion in 2000. Its size ranks in the top 100 funds in the world (Everest Consulting Association 2001). Annual payments to every resident of Alaska, including children, have grown steadily from a few hundred dollars per year in the early 1980s to about $1,900 in 2000 and 2001 (Table 9-5). North Slope oil is not the only source of fund revenue, but it constituted more than 95% of Alaska's oil production in 1999 and has been a major source of the fund's revenue since inception. Thus, assuming the population of the North Slope is 7,500 this year, the Permanent Fund Dividend program will produce approximately $13.5 million for the North Slope economy, much of that initially generated by past oil royalties.

Table 9-5 Permanent Fund Dividends, 1982-2001

Year	Amount
2001	$1,850.28
2000	$1,963.86
1998	$1,540.88
1996	$1,130.68
1994	$983.90
1992	$915.84
1990	$952.63
1988	$826.93
1986	$556.26
1984	$331.29
1983	$386.15
1982	$1,000.00

Source: Alaska Permanent Fund 2001

Economic Costs

There have been no economic valuation studies of effects on the physical, biotic, or human environment on the North Slope. That is, no research has translated positive and negative effects measured in physical units into how people value them in monetary terms. From the rich array of potential economic effects of oil and gas activities a few can be used to illustrate methods and types of data needed for economic evaluations: air pollution; altered spatial distributions of caribou and bowhead whales; and effects of long-lasting structures, roads, and trails on landscapes.

Air Pollution

A sample of time series emission data coupled with a diffusion model would help to establish where and how much air pollution North Slope residents are exposed to. These data can then be related to observed rates of morbidity and mortality. The economic value of lost days of work and medical expenses can then be tied to the rates of morbidity specific to the identified pollution loads. Estimated rates of mortality can be combined with estimated value(s) of a life (Freeman 1993, Viscusi 1992, EPA 1997). This cannot be done for the North Slope because records of emission are incomplete.

Subsistence Hunting

Oil exploration and development can alter the spatial distribution of caribou and the migration paths of bowhead whales. No studies, to our knowledge, demonstrate quantitatively whether spatial redistributions alter the sustainable equilibrium harvest or change the time it takes to harvest caribou or bowhead whales. The lack of data precludes estimating the dollar value of increased harvest time or of changed size of sustainable harvest. Other possible losses, such as the lowered quality of whale meat, are even more difficult to measure because of the lack of market prices. Finally, this method does not capture the economic cost of the reported greater risk involved in hunting when bowhead whales move farther from shore in response to seismic activity.

Passive Use Values

Some values cannot readily be directly or indirectly tied to market prices. For example, the benefits of wildlands include (Morton 2000) the scientific (protection of structure, composition and functioning of natural communities and entire landscapes as well as archeological and paleontological resources), the recreational, and the scenic. They also include protection of reservoirs of biological diversity, provision of ecological services, and spiritual (connection with "something beyond our modern society and its creations, something more timeless and universal"[66 FR 3729]), psychological (solitude; respite from machines, steel and concrete, crowding) and cultural and historical benefits, and "passive use values," as enumerated here (see also Figure 9-1):

- **option value**, maintaining for oneself or one's children the option of visiting wildland,
- **existence value**, the value of knowing a place exists independent of ever going there,
- **bequest value,** the value associated with bequeathing wilderness to future generations ("the hope of an undiminished future [66 FR 3730].")

The value of those benefits tends to increase as large, relatively undisturbed landscapes become scarcer. In the absence of markets for the goods and services illustrated above, people are studied using carefully designed surveys with methods developed by cognitive psychologists and market research specialist to elicit monetary values for quantitative changes in the qualitative features of an ecosystem (Cummings et. al. 1986, Diamond and Hausman 1994, Hanemann 1994, Hausman 1993, Mitchell and Carson 1989, Portney 1994). Many elements and values of wildlands can be roughly quantified, allowing those areas to be mapped according to the quantitative values they retain.

Of these different types of costs, the direct measurable costs associated with environmental effects are the easiest to quantify and are the best understood. In contrast, the committee could find no evidence of attempts to quantify the long-term future costs, passive-use values, or indirect costs of environmental effects. The information essential to assessing such effects is not even being collected. As a result, the full cost of oil development on Alaska's North Slope has not been assessed, quantified, or incorporated into decisions that affect use of public land. The section below illustrates a method for valuing passive-use values indirectly.

Incorporating Economic Costs of Environmental Effects into Decision Making

Incorporation of indirect, long-term, and passive use costs into an overall economic assessment of development would alter projections of economically recoverable oil and gas on public land on the North Slope. For example, the U.S. Geological Survey (USGS) periodically estimates the amount of recoverable oil in various areas of federally owned land on the North Slope. In doing so, the USGS generally projects the amount of oil that is economically recoverable from these lands given a particular price of oil and given a set of costs associated with development and transportation. By not fully accounting for indirect, future, and passive-use costs in its projections, the USGS underestimates the cost of development, which in turn inflates the amount of oil considered economically recoverable at a given market price.

This problem is most acute in light of uncertain, but plausible, effects that are likely to be irreversible and the traditional economic prescription: "Invest when expected benefits exceed expected costs" does not hold. The following example illustrates this fact. For the necessary geographic specificity, and because data are available, the Arctic National Wildlife Refuge is used as an example. The analysis can be applied to any undeveloped area. Development can include the construction of roads, pads, and other long-lived changes to the landscape. Before that, exploration creates seismic trails, of which about 15% are visible from the air after 15 years. Figure 7-7a captures the footprint of seismic lines laid down in 1985, more than 15 years ago. Many would regard seismic trails as having a negative effect on landscapes that accumulates as more trails are created. Given that about 4,000 km (2,500 mi) of lines or trails were surveyed during 1984-1985 in the Arctic National Wildlife Refuge, the appropriate setting is the value of further visual effects on the 600,000 ha (1.5 million acre) Arctic Coastal Plain.

The USGS has estimated that Arctic National Wildlife Refuge oil development would not be feasible if the price of North Slope oil is $15 per barrel ($0.36 per gal) or lower (because costs could not be covered by revenues). But this estimated minimum does not include any environmental costs associated with development or decommissioning (K. Bird, USGS, personal communication, 2001). At one point during the time this report was being prepared, the price of North Slope oil was around $17.50 per barrel ($0.42 per gallon) (*Wall Street Journal*, Jan. 24, 2002), and prices have fluctuated considerably before and since. Figure J-2 (Appendix J) illustrates a time series of crude oil prices whose level and fluctuations approximate North Slope oil prices.

Suppose, however, the expected price warranted development now, but that, in the future, the actual or expected price does not warrant further development and would not have justified the up-front exploration and development costs in the first place. Nevertheless, the environmental damage effects of seismic trails associated with the original exploration, together with the effects of roads and pads, persist.

Appendix J works out empirically the (stochastic dynamic programming) method (Arrow and Fisher 1974) used to analyze investment options under uncertainty with irreversibility.

Oil development might not be warranted from a social perspective, even if privately profitable; that is, if the private net benefits of development are positive. From a social perspective, expected private net benefits from oil development must be reduced by the accumulated environmental effects, including the loss of nonmarket values described in the section on wildland values in this chapter. The expected private value of oil development in the Arctic National Wildlife Refuge for alternative futures is calculated in Appendix J. A particular "future" is the chance that the price of oil will be a specific price above the break-even private cost of oil development. For any given future, there is an expected private net value of oil development. The important public-policy issue is whether the private net value for any given scenario is greater or less than the expected accumulated environmental costs of exploration and development. Because environmental costs have not been estimated in money terms, the analysis is done in terms of hurdles or thresholds. How large must the accumulated environmental costs be to offset the positive expected net private benefits of oil development? Equivalently, from a national perspective, if oil development in the Arctic National Wildlife Refuge (or elsewhere) should go forward, what is the highest value of accumulated environmental opportunities forgone that would *not* thwart this decision economically?

Employment

A main effect of the expansion of services and the capital improvement program by the NSB was the creation of borough jobs—in the expanded educational system, in construction for the capital improvement program, and in businesses that emerged—of the growing economy.

Two patterns characterize employment in the NSB (Table 9-6). First, the NSB has a disproportionate concentration of employment in government and government-funded activities. The borough government, school district, and capital improvement projects; Ilisagvik College; and the city, state, and federal governments together employ 61% of the workforce. A second pattern is the disproportionately low number of Inupiaq people employed in the oil and gas industry (although that is partly attributable to the larger percentages of Inupiaq young people: approximately 50% of North Slope Inupiat are under 20).

Table 9-6 North Slope Borough Residents' Employment by Sector and Ethnicity,* 1998

Employer	Inupiat	White	Other Minority	Total
NSB Government	509	217	151	877
NSB School district	134	108	47	289
Village Corporation	225	33	17	275
ASRC or subsidiary	90	26	16	132
NSB capital improvement	82	23	7	112
Service	28	36	19	83
Ilisagvik College	21	36	12	69
Private construction	44	14	8	66
City government	43	8	6	57
Transportation	14	17	12	43
Federal government	17	11	11	39
State government	9	19	7	35
Trade	14	9	12	35
Oil industry	10	4	2	16
Communications		4	1	5
Finance and insurance		1		1
Other	171	68	45	284
Total	1,411	634	373	2,418

*Includes only the 74% of the borough who responded to a survey (NSB 1999).

That few who live in the North Slope Borough are directly employed by the oil and gas industry has been noted for almost two decades (Kruse et al. 1983) and is supported by findings of both the NSB survey (NSB 1999) and the Alaska Department of Labor (Alaska Department of Labor and Workforce Development 2001). The NSB survey recorded only 16 local people of the 2,418 people surveyed who worked for petroleum companies. The Alaska Department of Labor reported that, for companies that collected and reported residency, of the 7,432 people who reported working on the North Slope in 1999 in the oil and gas sector, only 64 lived in the state's Northern Region—the Nome, North Slope, and Northwest Arctic boroughs (Alaska Department of Labor and Workforce Development 2001). Most of that group (50) were employed by two companies that are subsidiaries of the ASRC. Kruse et al. (1983) reported a variety of factors that affected both male Inupiaq willingness to work in the oil fields and the desire of companies in Prudhoe Bay to hire them.

An important factor is a desire to participate both in the cash economy and in the subsistence harvest. Borough jobs are preferable to oil industry jobs in part because they offer more flexibility, allowing time off for hunting. Those jobs also pay as well as the oil industry jobs do, and they are available locally instead of requiring extended periods of time away from home. In addition, Inupiat at Prudhoe Bay find they area small minority in a primarily white workforce that can sometimes express hostility toward Alaska Natives. The jobs available to the Inupiat often are seen by them as menial or as token jobs. And employment by the oil companies can threaten participation in the activity that provides the most status, hunting the bowhead whale. Another barrier is the lack of formal training and certification for skilled jobs.

Industry employees need specific skills from employees and often are unwilling to train workers unless there is some certainty that trainees are committed to remaining employed. Frequently, hiring takes place not on the North Slope at all, but in Fairbanks, Anchorage, or at company headquarters in the continental United States. Acknowledging that racism is difficult to document, Kruse et al. (1983, p. 138) recognized antagonism toward Inupiat among North Slope oil industry workers. Anecdotally, the committee heard from industry representatives that they hire Iñupiat only to have them not come to work reliably, and from Inupiat that they experienced discrimination in hiring and promotion. Whatever the causes, a main vehicles for funneling cash generated on the North Slope to residents of the NSB is functioning only marginally. Several programs have attempted to address this issue, but with limited success.

Because employment in the oil industry has been minimal, adaptation effects on North Slope residents are slight. However, if North Slope residents were to move increasingly into oil-field jobs there will be consequences (primarily on families) attributable to concentrated work scheduling (7 days on, 7 days off) (Forsyth and Gauthier 1991; Gramling 1989, 1996; Gramling and Forsyth 1987). Although the desire to participate in subsistence hunting is perceived as a barrier to employment on the North Slope, in the Gulf of Mexico the same work schedule allows employees extended periods to engage in traditional activities, such as fishing and shrimping (Gramling 1989).

ADAPTATION EFFECTS

Human systems are adaptable, even in extreme situations (Bettelheim 1943). The issue is not whether people will adapt—to externally generated perturbations or to internally negotiated threats and opportunities—but rather what consequences will accrue. As the various components of the human environment adapt to a development activity, new skills, knowledge, tools, and resources become available to support traditional activities. Two potentially problematic results also can occur.

First, the old patterns of behavior, economic activity, skills, and capital improvements, might be lost (sometimes quickly, sometimes across generations) because they are no longer relevant. The losses occur as Alaska Natives are entrained into a cash economy and increasingly need to use English as their primary language for communication about political, economic, and social changes. As they strive to become full partners in discussions about these changes, including those related to oil and gas development, it is difficult for them not to lose fluency in their traditional language, with its embedded knowledge of adaptation to the physical environment and of traditional relationships with the biota. Cable television, common in North Slope households, accelerates the cultural changes. Many North Slope residents reported to the committee their concerns about losing their traditional knowledge and practices and their way of life, despite their general reluctance to forgo the economic advantages they enjoyed.

Second, human and financial capital and nonrenewable resources can be, and usually are, actively committed to and consumed by the new development. If the new activity is not sustainable, when it declines or ceases communities or regions can be left less able to survive in their environment than they were before the new development came along. Freudenburg and Gramling (1992) call this *overadaptation.*

Oil and gas development has provided significant tax revenue to NSB residents. But the tax base is now declining, raising the question of whether the NSB can maintain its budget and its capital improvement program if oil and gas development diminish. Even in the short run—as newer, more efficient types of development are adapted and as older methods are phased out—the tax base for the NSB could decline more, leading to less support for the existing infrastructure and fewer borough jobs. Declines in borough revenue would require residents to pursue some mix of seeking oil industry jobs more aggressively, finding alternative sources of economic activity, relying more heavily on subsistence, migrating off the North Slope, or accepting a lower standard of living.

Another effect could precede actual declines in production. Increasingly, petroleum production on the North Slope is using new technologies, such as directional drilling, that occupy much smaller surface areas. This brings obvious environmental benefits, but also benefits the companies. Producing oil from a smaller space is cheaper because less gravel is mined and moved for pads and roads. Fewer shutdowns are needed to move the rigs and support equipment; there are fewer locations to deliver supplies to; fewer facilities to be built, heated, and maintained during production; and if rehabilitation is required, much smaller areas to be rehabilitated. Highly concentrated sites, however, can have lower assessed values, relative to the size of the subsurface structure they exploit, than huge surface complexes like Prudhoe Bay. So as big facilities are shut down and new, smaller facilities such as Alpine open, property tax revenues could decline significantly even as production increases.

The construction of a gas pipeline could forestall, at least for a time, the decline in tax revenue for the NSB. Commercial gas production would require the construction of new, taxable processing and transportation infrastructure, which presumably could remain operational in older fields even after they are no longer producing commercially feasible quantities of oil.
At some point, North Slope oil and gas will no longer be economically viable to recover. The potential for overadaptation by the communities now dependent on funds generated by this resource is a real one. The current standard of living—an economic benefit of oil and gas activity—could be impossible to maintain once petroleum activities cease.

The same trend toward smaller facilities and more environmentally friendly petroleum development is also likely to affect the ASRC, which is heavily invested in the oil-field-service industry. Smaller facilities will require less support during drilling and production, reducing the need for equipment and services. As with the NSB, there also is the potential for building infrastructure—private as opposed to publicly funded—that will be difficult to maintain once petroleum activity ceases in the region. The ASRC's primary assets appear to be its heavy investments in the energy services sector and its potentially mineral rich lands. Natchiq is a family of more than 20 diverse and strategically aligned companies and subsistence that operates in Alaska, Canada, the U.S. Gulf Coast and the rest of the continental states, and Russia to support the oil and gas industry. It offers exploration to development, construction to production, and maintenance services, and the Natchiq companies employ nearly 4,000 people (ASRC 2001, p. 14). As Freudenburg and Gramling (1998) have noted, however, in examining the petroleum support sector in the Gulf of Mexico, a support sector that has fiscal linkages primarily to one sector (petroleum extraction and production) is likely to mirror the performance of that sector, both as it rises and as it falls.

FINDINGS

- Without the North Slope petroleum discoveries and development, the North Slope Borough, the Alaska Native Claims Settlement Act, and the Arctic Slope Regional Corporation would not exist. The emergence of those structures has caused major, significant, and probably unalterable changes to the way of life in North Slope communities. The primary vehicle of change is revenue that has flowed into communities from NSB property taxes on petroleum infrastructure. Oil development has resulted in assets for North Slope residents that exceed $1 million per capita. Asset value per capita, excluding petroleum structures, exceeds $100,000. Many North Slope residents view the changes positively. However, social and cultural changes of this magnitude are not without costs in terms of social and individual pathology.
- Offshore exploration and development and the announcement of offshore sales have resulted in perceived risks to Inupiaq culture that are widespread, intense, and themselves are accumulating effects. The people of the North Slope have a centuries-old nutritional and cultural relationship with the bowhead whale, and most view offshore industrial activity as a threat to bowheads and thereby to their cultural survival. They have generally supported onshore development, however, subject to adequate environmental controls.
- Proposals to explore and develop oil resources in the Arctic National Wildlife Refuge have resulted in perceived risks to Gwich'in culture in Alaska and the Yukon Territory that are widespread, intense, and themselves are accumulating effects. The Gwich'in have a centuries-old nutritional and cultural relationship with the Porcupine Caribou herd and oppose new onshore petroleum development that they believe threatens the caribou.
- The current standard of living for North Slope residents will be impossible to maintain unless significant external sources of local revenue are found.
- There has been little direct employment of North Slope residents by the petroleum industry. Several programs have addressed this issue, but their success has been limited.
- Many activities associated with petroleum have changed the landscape in ways that have had aesthetic, cultural, and spiritual consequences and those consequences will increase as the use of these facilities and infrastructure declines.

- Wildland values over more than 2,600 km^2 (1,000 mi^2) of the North Slope have been compromised by oil development. The potential for further loss is at least as great as what has already occurred as development expands over the next 20-50 years, although the nature and degree will vary. Some effects will dissipate when oil activities end, but many structures now on the North Slope are likely to remain long after industrial activities cease, rendering their effects on wildlands essentially permanent.
- There is no integrated, North Slope-wide framework for wildland evaluation, mapping, ranking, planning, and analysis of effects. There has been a steady erosion of wildland values over a vast area through a series of individual, project-by-project decisions by different state and federal government agencies.
- Environmental impact statements do not in general evaluate the individual or the accumulation of effects of development proposals on wildland values in a meaningful way.
- The common practice of describing the effects of particular projects in terms of the area directly disturbed by roads, pads, pipelines, and other facilities ignores the spreading character of oil development on the North Slope and the consequences of this to wildland values. All of these effects result in the erosion of wildland values over an area far exceeding the area directly affected. The loss of wildland values has not been assessed in terms of the total area affected.
- Although there are rigorous means of evaluating wilderness values, academic and agency researchers have paid insufficient attention to developing meaningful, qualitative, and quantitative metrics for evaluating wildlands and incorporating findings into the decision-making process. There is inadequate knowledge of the economic value of North Slope wildlands.
- Oil prices will depend primarily on circumstances far from the North Slope. The social cost of alterations to the landscape caused by oil and gas development that are long-lived or irreversible, such as seismic trails and gravel roads and pads, will continue long after the private returns from oil and gas extraction on the North Slope cease. Therefore, the social costs of development in new areas of public land should play a central role in determining whether exploration and extraction in previously undeveloped public lands are economically warranted.
- The full economic costs associated with environmental effects of oil development on Alaska's North Slope have not been quantified.
- Human-health effects, including physical, psychological, cultural, spiritual, and social, have not been adequately addressed or studied.
- A slope-wide, jurisdictionally coordinated framework for wildland evaluation, mapping, ranking, impact analysis, and planning would help decision-makers identify conflicts, set priorities, and make better-informed decisions.

RECOMMENDATIONS

- Research should identify the specific benefits and threats that North Slope residents believe are posed to their ways of life by oil and gas development. This research should target how much oil and gas activities, as distinguished from other factors, are associated with rising levels of sociocultural change. Research on the North Slope, regardless of its subject matter, needs to occur as a cooperative endeavor with local communities. Traditional and local knowledge and language involves rich, detailed information about the physical environment, the biota, and the human communities of the North Slope. That information should be incorporated into research—from identification of topics and study design through interpretation and presentation of results.

- The research community should focus on developing ways to translate theoretical wildland concepts and values into concrete terms that can be used in environmental assessments and other contexts.
- Research should identify the specific human-health effects (physical, psychological, cultural, spiritual, social) that North Slope residents believe they experience as a result of oil and gas development.

10

Filling Knowledge Gaps

The Committee on Cumulative Environmental Effects of Alaskan north Slope Oil and Gas Activities was charged with identifying gaps in knowledge that hinder identification of cumulative effects and with assessment of their causes and importance. Those tasks were made more difficult because data were not always available or were not coordinated or comprehensive, although much is known about the region. This chapter discusses the shortcomings of the data and ways to improve the collection and organization of new information to help future assessments. Specific needs to inform decisions about oil and gas activities on the North Slope also are described.

A great deal of time and effort had been invested in studying North Slope environments and assessing the effects of oil and gas activities there. Some of the research recommendations that follow are for new investigations, but many of them represent a sharpening of the focus and the emphasis of current efforts.

NEED FOR COMPREHENSIVE PLANNING

Decisions about the conditions for and requirements of permitting industrial activities on the North Slope are made by many federal, state, and municipal agencies. Communication and coordination among those agencies have been weak and sporadic. Permitting decisions generally have been made one case at a time without a comprehensive plan to identify the scope, intensity, direction, or consequences of industrial activities that are judged appropriate and desirable. Similarly, the minimal rehabilitation of disturbed habitat has occurred without an overall plan to identify land-use goals, objectives to achieve them, performance criteria, or monitoring requirements. Little consideration has been given to how different future trajectories would be viewed by different groups, including North Slope residents.

In particular, there has been no comprehensive estimate of the costs of dismantlement and removal of infrastructure and subsequent restoration and rehabilitation (DRR) of affected North Slope areas. This is important because although DRR is assumed in some permits and plans, it will almost surely cost much more than the amount of money available. Extrapolation from estimates for individual project plans suggests a total cost of billions of dollars. However, existing state and federal bonding requirements are not even remotely sufficient to underwrite potential DRR costs on the North Slope. Because the obligation to restore abandoned sites is unclear and the financial resources to do so are so uncertain, the committee judges it likely that, absent a change in those constraints, most the disturbed North Slope habitat will never be rehabilitated or restored. What is needed is a slope-wide land-use plan and an understanding of the likely costs and effectiveness of various DRR approaches.

The quality, accessibility, and extent of data to evaluate effects and their accumulation also is inadequate. In many cases, the committee did obtain necessary data, and we are grateful for the cooperation and efforts of state, federal, and local governments; industry; environmental groups; individual researchers; the North Slope Borough, and interested members of the public. But often the committee had difficulties in obtaining data it needed. Sometimes the data did not exist, and other times the data were less useful than they could have been. The reasons for these difficulties included confidentiality, particularly for identifying the locations of seismic exploration; a failure to analyze information from agency or industry files; the lack of comparability of data collected by various agencies; and the lack of long-term data sets that could be used to assess or anticipate future accumulating effects. For example, most of the data acquired from water-quality monitoring programs, which are required by discharge permits, are retained by the principal permitting agency, the Environmental Protection Agency, and are not readily available. Records also are kept by individual operators, but they are not summarized, and there are few annual reports.

Two kinds of comprehensive planning are needed to overcome these shortcomings and to better explain and manage the environmental effects of oil and gas activities on Alaska's North Slope and their accumulation. The first is for a comprehensive slope-wide land-use plan to guide industrial development and assist in planning for the eventual departure of the oil and gas industry from the region. The plan should identify land-use goals and specify restoration and rehabilitation objectives to achieve them. It should include specific performance criteria and monitoring requirements tied to restoration and rehabilitation objectives, and it should provide an inventory of current facilities and gravel fill, including an assessment of the nature and extent of contamination. It should specifically include plans for decommissioning, abandonment, and restoration and rehabilitation once oil and gas production is no longer viable. Even if changing oil prices, new hydrocarbon discoveries, disintegrating infrastructure, changing political arrangements, and other unforeseen factors were to make such a plan obsolete before it could be implemented, the exercises would provide a shared vision of goals for the North Slope, and help to identify areas where knowledge is inadequate and would thus help to guide research and monitoring.

The second need is for a coordinated and comprehensive research plan. This should include the following:

- A regional assessment of ecological and human values that have various degrees of sensitivity to disturbance with a view to ranking their importance and the urgency of addressing them.
- Important research questions developed through collaborative efforts of scientists, local communities, industry, interested members of the public, and regulatory agencies.
- Identification of key indicators of environmental status and trends and how they will be measured.

To increase the likelihood that the research would be of the broadest usefulness in decision making and to have the greatest scientific validity, the following approaches should be incorporated into the research:

- Traditional and local knowledge, especially information gathered by subsistence hunters, should be incorporated into the research plan at all stages of research, from study design through interpretation and presentation of the results.
- Provision should be made for data gathered and managed by various agencies to be comparable and accessible, using the same units and standards of data quality wherever possible. For example, geographic information systems (GIS) are powerful planning tools to help in developing a slope-wide land-management plan. A single site should be established where data are stored and can be accessed.
- Where possible, a hypothesis to be tested should be identified and appropriate controls established before data are collected.
- Thorough, independent peer review should be conducted at all stages of the research, from study design to publication of results.

SCIENTIFIC INFORMATION NEEDS

Ecosystem-Level Research

Most ecological research in the Prudhoe Bay region has focused on local studies of the behavior and population dynamics of animal species. Patterns and processes at landscape scales, as well as nutrient cycling and energy flows, have received relatively little attention. Nevertheless, the research that has been done has identified the need for, and importance of, studies of population dynamics over large areas and the need to assess how industrial activities on the North Slope are affecting the productivity of tundra ecosystems. Alterations of flow patterns of water across the Arctic Coastal Plain, thermokarsting of tundra adjacent to roads and off-road pathways, and changes of albedo attributable to dust are all likely to influence plant community composition; rates of photosynthesis and decomposition; and efficiencies of energy transfer between plants, herbivores, and carnivores. Thus, tundra within an oil field is likely to differ in many ways from that in an unaffected ecosystem, yet the extent of the differences and the processes that cause them are largely unknown.

To assess these differences, protected areas similar to those established by the National Science Foundation's Long Term Ecological Research (LTER) program, accessible to researchers areas should be established in comparable areas within and outside the industrial complex. Currently the LTER site closest to the area of concern is at Toolik Lake site in the foothills of the Brooks Range, about 250 km to the south. Long-term studies should be initiated to assess the influence of industrial activities on fluxes of energy and nutrients in these systems. Particular attention should be paid to those processes most likely to be altered with the objective of identifying ways to reduce the accumulation of undesirable effects, whether by avoiding particularly vulnerable areas or by adjusting the nature of activities to reduce the degree to which ecosystem processes are affected.

Human-Health Effects

The effects of oil and gas activities on human health have not been well documented. Some human-health effects of encroachment of industrial civilization into Alaska Native communities are well known, such as the increased use of alcohol and drugs, increased obesity, and other societal ills. But on the North Slope, it is not possible with available data to say to what degree they are the direct result of oil and gas activities. Other concerns are widespread among Native residents of the North Slope, including concerns about air pollution, contamination of water and food, and noise. To some unknown degree the increased financial resources from oil taxes and royalties have balanced adverse health effects by significantly improving the quality and availability of medical care on the North Slope. The human-health effects of oil and gas activities constitute one of the areas in greatest need of additional reliable information.

Offshore Oil Spills

The committee heard many comments indicating that oil spills are a grave concern among North Slope residents, especially the threat of a large offshore spill. Although there have been no large oil spills in waters off the North Slope, they are such a major concern that we make some comments here about possible research into mitigating their effects, recognizing that this is somewhat beyond our charge. The results of such research would help to refine future assessments of how the effects of major spills accumulate.

Considerable research has been done on methods of cleaning up spills and on mitigating some of their effects (see e.g., Allen 1998, 1999, 2002; Lindstedt-Siva 1992; NRC 1989, 2002). This committee has neither deliberated about the most important research topics for oil-spill cleanup and mitigation, nor has it attempted to reach a consensus on whether, when, and how experimental oil spills might be used in such a research program. Nonetheless, research in a variety of areas seems to be warranted, including the use of noise to move bowhead whales—and perhaps other marine mammals—away from areas affected by a spill. It would also be useful to have the results of research on the effectiveness and environmental liabilities and advantages of nonmechanical methods of cleaning up oil spilled in the sea (e.g., dispersants, in-situ burning), especially in broken-ice conditions. Such research might be of great value in decision making and in formulating the comprehensive plans that the committee identified as being needed.

Research and Human Communities

People and their communities interact with information needs both as consultants and as subjects. As a result, information about the accumulation of effects is missing or sparse in several areas. Therefore, if better assessment is to occur, the following areas need attention:

- Research on the North Slope, regardless of its subject matter, should occur as a cooperative endeavor with local communities. Traditional and local knowledge of the physical environment, the biota, and the human communities on the North Slope is comprehensive and important. This information should be incorporated into research efforts, from the identification of topics and study design through interpretation and presentation of results.
- Balancing economic benefits of oil and gas activities against loss of traditional knowledge and language often is a dilemma for North Slope residents. Research should identify the specific lifestyle benefits and threats that North Slope residents attach to oil

and gas industrial activity. This research should target how much oil and gas activities, as distinguished from other factors, are associated with increasing sociocultural change.

- Research should establish how oil and gas activities and their effects—those deemed positive or negative—have influenced community and individual behavior.
- Research should identify the direct and indirect monetary rewards and costs (including passive-use values) associated with petroleum development on the North Slope. The research should describe rewards and costs for North Slope residents as well as for nonresidents, and it should qualitatively describe effects that cannot be converted to money.
- Research should be conducted on how to best manage effects of rapid social, economic, cultural, and spiritual changes for the Inupiat and Gwich'in of the North Slope and Alaska.

Zones of Influence

Technological developments have greatly reduced the "footprint" of new industrial activities on the North Slope. For example, horizontal drilling and pad refrigeration allow well-heads to be spaced closely on smaller pads. The use of ice roads allows exploration in the winter when its effects on tundra vegetation are greatly reduced. Gravel pads generally are now constructed only for successful exploration wells, and many wells need not be served by permanent gravel roads. Underground injection has eliminated the need for reserve pits to accommodate wastes. Pipelines are still required, however, although fewer than formerly.

Clearly, those advances have greatly reduced the incremental direct effects of new industrial activities on North Slope environments and organisms. Nevertheless, the effects of industrial activities are not limited to the footprints or their immediate vicinity. The committee has identified a variety of influences that extend varying distances from actual facilities. They range from effects on animals that are attributable to gravel roads and pads and that extend a few kilometers, to the influence of industrial structures on visual aspects of the landscape, which can extend as far as 100 km (60 mi).

The examples identified by the committee do not list all of the ways that consequences of activities extend beyond the physical footprint because there are no data to estimate how, why, and to what distance many receptors could be influenced. The full accumulation of the effects of oil and gas activities to date, as well as in the future, cannot be assessed without much better quantitative information about the ways in which effects extend for varying distances.

Current activities should be studied to identify zones of influence of industrial activities and structures on various components of the North Slope environment. Future industrial activities and structures should be studied to generate data showing how and why various receptors are affected by those activities and the distances over which those effects occur.

Air Contamination and its Effects

Air pollution on the North Slope is a concern to residents, and its effects could accumulate. There has been little research to quantify the contribution of local emissions from oil and gas facilities or to determine how local and regional air masses and their contaminants interact. The lack of predevelopment baseline data further hampers assessment of locally and distantly produced pollution on North Slope air quality.

No monitoring system (except for tracking of priority pollutants from 1986 through 2002 at a limited number of sites) has been established to provide a quantitative baseline of spatial and temporal trends in North Slope air quality. The lack of adequate information limits the accuracy and precision of assessments of past and predictions of future accumulation of effects. Given local concerns about air quality and its perceived effects on human health, studies should be undertaken to distinguish between locally derived emissions and long-range transport, to determine how they interact, and if necessary to monitor potential human exposure to air contaminants.

Seismic Exploration and Other Off-Road Traffic

Networks of seismic and other off-road vehicle trails as well as ice roads and ice pads cover extensive areas of the tundra. They are a concern because of the damage they do to vegetation and their visibility from the air. The development of new seismic data-acquisition methods, such as lightweight, rubber tracked equipment, might reduce the effects of those activities by reducing the weight, tracks, or number of vehicles used, but the degree to which tundra damage will be reduced is unknown.

The current regulations governing minimum snow depth (average 15 cm [6 in.]) and frost penetration (30 cm [12 in.]) to allow seismic activities on the tundra are not based on research and do not account for variations in snow depth caused by topography or differential drifting. Thus, the degree of protection they provide to tundra is unknown. Much of the information regarding the location of seismic activities is considered proprietary and is not available to researchers or the public. This information is critical for determining the areas affected and the long-term effects of these activities.

Studies of the effects and persistence of the trails of off-road vehicles are needed, including their long-term visibility from the air. Studies are needed to determine the amount of snow and the frost penetration required to adequately protect the tundra from the effects of seismic exploration.

Exploration is expanding beyond the current area of activity, both southward into the foothills of the Brooks Range and westward well into the National Petroleum Reserve-Alaska (Chapter 5). New areas for oil and gas exploration are likely to differ substantially from current areas of activity. To understand, predict, and manage cumulative environmental effects in the new areas, their environments need to be characterized. This should include descriptions of topography; permafrost conditions; sand, gravel, and water availability; hydrological conditions; and biotic communities.

Caribou and Bowhead Whales

A better understanding is needed of the seasonal habitat requirements of caribou, natural environment constraints, details of the physiology of reproductive tradeoffs, and how disturbance affects them in the Arctic.

Studies are needed to determine the qualitative relationship between the noise generated by offshore operations and the migratory and acoustic behavior of bowhead whales. The studies should include analysis of the effects of multiple noise sources. Better information is also needed about the degree to which bowheads feed in the Alaskan portion of the Beaufort Sea.

Consequences of Water Withdrawals

Water for ice roads, pads, and other purposes is taken from lakes on the North Slope. Because most lakes in the existing development area between the Colville and Sagavanirktok rivers are less than 1.8 m (6 ft) deep, and hence freeze to the bottom, few fish are present and the impacts on them have been minimal. As development spreads into regions with deeper lakes, such as the Colville delta and the eastern portion of the National Petroleum Reserve-Alaska, there is greater potential to affect fish populations within lakes. Under current Alaska Department of Fish and Game policy, water withdrawals from fish-bearing lakes are limited to 15% of the estimated minimum water volume during winter to retain most of the water for wintering fish. The 15% criterion was set arbitrarily in the absence of data to support an alternative, and no research has been conducted to determine what the effects of withdrawals are on populations of invertebrates in the lakes and, hence, food supplies for vertebrates. As of late 2002 there were no restrictions on removal of water from fishless lakes.

An initial study of the 15% criterion should determine the degree to which that criterion prevents harm to fish and invertebrates. A study of the effects of withdrawing water from lakes without fish should be conducted to assess the degree to which current water use affects biota associated with these water bodies.

Dealing with Uncertainties

Actions undertaken to identify and reduce the undesirable effects of interactions among effectors and receptors should greatly improve the quality and quantity of data in future decision-making. However, the information will never be sufficient to eliminate uncertainty in future problem-solving. Some species, such as marine mammals and fishes, are intrinsically difficult to study. Detecting even fairly important changes in their population densities and demographic parameters could be impossible, no matter how much money is available to study them. Also, adequate controls could be impossible to establish. Informative manipulations of populations of rare and endangered species are legally constrained. Experimental oil spills could be politically unacceptable. Distinguishing between changes attributable to specific oil and gas activities and those that are the results of other causes is often difficult because multiple factors typically influence the receptors of interest. Finally, there is uncertainty about reference states or conditions because environmental factors, such as climate change over time and space.

Some of the above problems cannot be solved, but scientific uncertainty can be usefully described by an analysis of the power of the statistical tests being used. When analyzing data collected to test a hypothesis that X has an effect on Y, two kinds of errors are possible. First, one can conclude falsely that there is an effect when actually there is none (a Type I error); second, one can conclude falsely that there is no effect when actually there is one (a Type II error). The likelihood of making either kind of error can be reduced by appropriate analyses, but reducing the likelihood of making one type of error always increases the likelihood of the other. The only way to reduce the likelihood of making both kinds of errors simultaneously is to have more data, either through larger or more samples.

To assess the consequences of making a Type II error, it is helpful to state the magnitude of the effect that could have gone undetected. This is equivalent to asking, "If, on the basis of a statistical test at a chosen significance level, it is concluded that the action has no effect, then how large would an effect have to be for the test to detect it?" The answer is often that the magnitude of statistically undetectable effects is much larger than anyone would have expected. This question should be explicitly considered and described in designing studies to assess the effects of activities already undertaken and the likely consequences of proposed activities on the North Slope. In addition, final results should be accompanied by a statement of the magnitude of effects that would have escaped detection. Those uncertainties should be clearly communicated to decision makers. More detailed discussion of these and related topics is presented in work by the National Research Council (1995) and Simberloff (1990).

No matter how much information would be desirable, decisions often cannot be deferred. How, then, can the best use be made of the information that is available to inform decision-making? This difficult challenge—making environmental decisions in the face of uncertainty—was discussed in detail (with a focus on the Endangered Species Act) by the National Research Council (NRC 1995). The general topic of environmental decision-making under uncertainty often appears under the rubric of the precautionary principle, which says in effect that when there is doubt one should err on the side of the environmental resource. In practice, such an admonition often is not helpful as a guide for making real policy or management decisions. Precaution is a continuous variable, and one person's precaution is another's reckless disregard. The central problem is to characterize people's valuation of risks and rewards and incorporate them into frameworks for risk assessment and management.

11

Major Effects and Their Accumulation

The committee on the Cumulative Environmental Effects of Alaskan North Slope Oil and Gas Activities was charged with reviewing information about oil and gas activities on Alaska's North Slope with the objective of assessing their known and probable cumulative effects of those activities on the physical, biotic, and human environments of the North Slope and the adjacent marine environment. The committee also was directed to assess future cumulative effects, based on its judgment of likely changes in technology and the environment. The committee attempted to be thorough in its analyses to reduce the likelihood that important effects—and how they might accumulate—would be undetected. The results of the committee's investigations are detailed in Chapters 6 through 9.

The importance of effects is perceived differently by different individuals or groups. The committee is not aware of a satisfactory way of attributing some absolute degree of importance to effects, and so it attempted to describe the basis on which it assessed importance of the effects. For example, it considered ecological consequences, importance given by North Slope residents, irreversibility, degree of controversy, and economic consequences for North Slope residents.

As described in Chapter 10, there was considerable difficulty with assembling information for some analyses, both because of gaps in data and because of the inaccessibility of some information. Nevertheless, the committee did identify important effects of industrial activities on the North Slope and how they accumulate. Details that support its judgments are provided earlier in the report.

The committee based its projections of future accumulation of effects on a 50-year scenario that assumes political stability and world prices for petroleum products that support the continued expansion of oil and gas activities westward across the Arctic Coastal Plain and southward into the foothills of the Brooks Range (Chapter 5). Some effects are not yet manifest; they will accumulate as consequences of past and current activity. They would occur even if North Slope oil and gas exploration and production ended today. Other effects will accumulate as a result of new activities. Mostly, they will involve increases of current effects, but new effects are likely to be created as well—both by the expansion and by the ultimate retraction of industrial activity.

Assessments of future effects are problematic because of the connection between world politics and the oil market. It is possible to guess, but no one knows for certain how the events of the next decade will affect oil prices or availability. Moreover, future industrial activities will be carried out in a physical climate that will change in ways that are difficult to predict. Nevertheless, if oil activity expands and a gas pipeline is built, the continuing accumulation of effects is virtually certain.

Many laws and regulations affect oil and gas exploration, development, production, and transportation, and many federal, state, and local government offices are involved (see Appendix I). Regulatory oversight can be critical in reducing the accumulation of undesirable effects. The committee's predictions of future effects and their accumulation assume that regulatory oversight will continue at least to the extent of the recent past.

All of the effects identified by the committee accumulated as the result of the actual spread of industrial activity on the North Slope or as responses to the news that such activity was likely to occur.

Since the 1960s, industrial activity on the North Slope has grown from a single operational oil field at Prudhoe Bay to an industrial complex that stretches from the Alpine field near the mouth of the Colville River on the west to the Badami oil field, about 39 km (23 mi) from the borders of the Arctic National Wildlife Refuge in the east. In 2001, oil development on the North Slope consisted of 19 producing fields connected to the rest of Alaska by a highway and a pipeline that cross the state. The network consists of 115 gravel drill sites, 20 pads with processing facilities, 115 pads with other support facilities, 91 exploration sites, 13 off-shore exploration islands, 4 off-shore production islands, 16 airstrips, 4 exploration airstrips, 1,395 culverts, 960 km (596 mi) of roads and permanent trails, 450 mi (725 km) of pipeline corridors, and 219 mi (353 km) of transmission lines. Gravel roads and pads cover more than 3,500 ha (8,800 acres), not including the Trans Alaska Pipeline and the Dalton Highway, and gravel mines have affected nearly 2,600 ha (6,400 acres). Ubiquitous permafrost requires that this infrastructure not thaw its own foundations, imposing an architecture with environmental consequences of it own. Massive gravel fills under roads and other work surfaces are required to raise them 1.8 m (6 ft) above the tundra. Heated buildings and pipeline networks must be elevated on pilings, and the closely spaced oil wells are extensively refrigerated. This network has grown incrementally as new fields have been explored and brought into production (Chapter 4). For a variety of reasons, nearly all roads, pads, pipelines, and other infrastructure—whether in current use or not—are still in place and are likely to remain into the future. Their effects are manifest not only at the physical footprint itself but also at distances that vary according to the environmental component affected. Effects on hydrology, vegetation, and animal populations occur at distances up to several kilometers, and cumulative effects on wildland values—especially visual ones—extend much farther, as can the effects on marine mammals of sound caused by some offshore activities. All effects attributable to the structures and the activities associated with them accumulate, and many will persist as long as the structures remain, even if industrial activity ceases.

SOCIAL CHANGES IN NORTH SLOPE COMMUNITIES

Without the discovery and development of North Slope petroleum, the North Slope Borough, the Alaska Native Claims Settlement Act, and hence the Arctic Slope Regional Corporation, either would not exist or would bear little resemblance to their current form. Petroleum development has resulted in major, significant, and probably irrervisible changes to the way of life on the North Slope (Chapter 9). The primary vehicle of change is revenue that has flowed into communities from property taxes levied by the North Slope Borough on the petroleum industry's infrastructure. Many North Slope residents view many of these changes positively. However, social and cultural changes of this magnitude inevitably have been accompanied by social and individual pathology. Those effects accumulate because they arise from several causes, and they interact. As adaptation occurs, the communities and the people who make them up interact in new and different ways with the causes of social change.

Interference With Subsistence Activities

Offshore exploration and development and the announcement of offshore sales have resulted in perceived risks to Inupiaq culture that are widespread, intense, and themselves constitute a cumulative effect (Chapter 9). The people of the North Slope have a centuries-old nutritional and cultural relationship with the bowhead whale and caribou. Most view offshore industrial activity—both the observed effects and the threat of a major oil spill—as threatening the bowhead population and, thereby, their cultural survival. Noise from exploratory drilling and marine seismic exploration has caused fall-migrating bowheads to avoid noise above 117-135 dB. The distances over which the migratory pathways of the whales have changed are not yet known, but the deflections forced subsistence hunters to travel greater distances than formerly to encounter whales. The results are increased risk of exposure to the dangers of the open sea and the increased likelihood that whale tissues will deteriorate before carcasses are landed and butchered. Recently the Alaska Eskimo Whaling Commission has reached agreements that restrict seismic-vessel operations during the fall hunting period, but they are renegotiated annually.

The threat of a major oil spill also is viewed with trepidation by the coastal Inupiat, even though no such spill has yet occurred. These threats are accumulate because they interact with other factors such as climate change and because they are repeated with every new lease sale.

On-land subsistence activities have been affected by the reduction in the harvest area in and around the oil fields. The reductions are greatest in the Prudhoe Bay field, which has been closed to hunting, and in the Kuparuk field, where the high density of roads, drill pads, and pipelines inhibits travel by snow machine. The reduction in area used for subsistence is most significant for Nuiqsut, the village closest to the oil-field complex. Even where access is possible, hunters are often reluctant to enter oil fields for personal, aesthetic, or safety reasons. There is thus a net reduction in the available area, and this reduction continues as the oil fields spread.

Although there has not yet been industrial activity in the Arctic National Wildlife Refuge, proposals to explore and develop oil resources there have resulted in actual and perceived risks to the Gwich'in culture that are widespread, intense, and themselves are accumulating effects (Chapter 9). The Gwich'in have a centuries-old nutritional and cultural relationship in Alaska and the Yukon Territory with the Porcupine Caribou Herd. Most view petroleum development in the 1002 Area of the Arctic National Wildlife Refuge as a threat to the herd and, thereby, to their cultural survival. The threats accumulate because there have been repeated attempts to develop the area and there is continuing pressure to do so.

Aesthetic, Cultural, and Spiritual Consequences

Many activities associated with petroleum development have changed the North Slope landscape in ways that have had aesthetic, cultural, and spiritual consequences that accumulate.

The consequences have increased along with the area of tundra affected by development, and they will persist for as long as the landscape remains altered.

Roads, pads, pipelines, seismic-vehicle tracks, and transmission lines; air, ground, and vessel traffic; drilling activities; landfills, housing, processing facilities, and other industrial infrastructure have reduced opportunities for solitude and have compromised wildland and scenic values over large areas (Chapter 9). The structures and activities also violate the spirit of the land, a value that is reported by some Alaska Natives to be central to their culture. Given that most of the affected areas are not likely to be rehabilitated or restored to their original condition, those effects will persist long after industrial activity has ceased on the North Slope.

DAMAGE TO TUNDRA FROM OFF-ROAD TRAVEL

The tundra on the North Slope has been altered by extensive off-road travel, some of which may not be directly related to oil and gas activity. Networks of seismic-exploration trails, ice roads, pads, and all-terrain vehicle trails cover large areas. The currently favored three-dimensional seismic surveys require a high spatial density of trails, and the potential damage is substantial because larger camps and more vehicles are used than were used previously for two-dimensional exploration. Although the technology for acquisition of seismic data continues to improve, damage has not been totally eliminated, and some areas have been explored repeatedly—sometimes revisits to gather more complete data using new and better technologies; sometimes to gather data already gathered by a competitor who did not share the proprietary information.

Some seismic-exploration effects accumulate because areas are revisited before the tundra recovers from previous surveys. Seismic exploration can damage vegetation and cause erosion, especially along stream banks. In addition, because seismic trails are readily visible, especially from the air, they affront the residents and degrade the visual experience of the landscape. Data do not exist to determine the period that the damage will persist, but some effects are known to have lasted for several decades (Chapter 7).

Seismic exploration is expanding westward into the National Petroleum Reserve-Alaska and southward into the foothills of the Brooks Range. Current technology and government regulations will not prevent damage to the tundra. Moreover, exploration will be conducted in regions where the topography is more complex and where permafrost conditions are more variable and less well known than on the Arctic Coastal Plain, where most exploration has been done (Chapter 5). The nature and condition of permafrost in the Brooks Range foothills is poorly characterized, and the hilly topography increases the likelihood that vehicles will damage vegetation, especially on knolls and riverbanks, causing increased erosion, exposing bare soil, and promoting development of thermokarst. This exploration will probably be carried out in a warming climate, with milder winter temperatures. It is hard to predict the consequences of vehicular traffic in winter on tundra under those conditions.

ROADS

Roads have had effects as far-reaching and complex as any physical component of the North Slope oil fields. In addition to covering tundra with gravel, indirect effects on vegetation are caused by dust, roadside flooding, thermokarst, and roadside snow accumulation. The effects accumulate and interact with effects of parallel pipelines and with off-road vehicle trails. The measurable direct effects covered approximately 4,300 ha (10,500 acres) in the developed fields, not including indirect effects of the Dalton Highway. Roads also alter animal habitat and behavior and can increase access of hunters, tourists, and others to much of the region; enhance communication among communities; and increase contacts between North Slope communities and those outside the area.

EFFECTS ON ANIMAL POPULATIONS

Animals have been affected by industrial activities on the North Slope (Chapter 8). Bowhead whales have been displaced in their fall migration by the noise of seismic exploration. The full extent of that displacement is not yet known. Some denning polar bears have been disturbed. The readily available supply of food in the oil fields has resulted in the persistence of higher-than-normal densities of predators, such as brown bears, arctic foxes, ravens, and glaucous gulls. Those animals are important predators on nests, nestlings, and fledglings of many bird species, and the reproductive success rate of some bird species in the developed parts of oil fields has been reduced to the extent that it is insufficient to balance mortality. Serious efforts have been made, in the form of educating workers, fencing dumps, and using animal-proof waste receptacles, to reduce the amount of supplemental food available to predators. Those efforts have been only partly successful; some predators have become expert at accessing garbage and it is difficult to persuade people to stop feeding them.

Reproductive rates of some bird species are, at least in some years, insufficient to balance mortality. That is, they are "sink populations" whose densities have been maintained only by steady immigration from "source" areas where reproductive rates exceed mortality. As industrial activities continue to expand, increasing numbers of sink areas are likely to be created and more and more source areas are likely to be depleted. Ecology theory and empirical data indicate that populations can decline suddenly if source areas are significantly degraded.

How industrial activity interacts with source-sink population dynamics is difficult to assess because local population studies alone, no matter how detailed, cannot detect all effects. To anticipate and predict population collapse from disrupted source-sink population dynamics, analyses must focus on those species most likely to be affected, and studies must gather specific kinds of data. The number of vulnerable species cannot be determined because demographic information does not distinguish source and sink habitats, but several species of birds and mammals could be adversely affected.

As a result of conflicts with industrial activity during calving and an interaction of disturbance with the stress of summer insect harassment, reproductive success of Central Arctic Herd female caribou in contact with oil development from 1988 through 2001 was lower than for undisturbed females, contributing to an overall reduction in herd productivity. The decrease in herd size between 1992 and 1995 may reflect the additive effects of surface development and relatively high insect activity, in contrast to an increase in the herd's size from 1995 through 2000, when insect activity was generally low. Although the accumulated effects of industrial development to date have not resulted in large or long-term declines in the overall size of the Central Arctic Herd, the spread of industrial activity into other areas that caribou use for calving and relief from insects, especially to the east where the coastal plain is narrower than elsewhere, would likely result in reductions in reproductive success, unless the degree to which it disturbs caribou could be reduced. Without specific information on the exact nature of future activity and its precise distribution, it is not possible to predict to what degree the migrations and population sizes of caribou herds would be affected.

OIL SPILLS

Major oil spills have not occurred on the North Slope or in adjacent oceans as a result of operations there. There have been three major spills from the North Slope segment of the Trans-Alaska Pipeline. Many small terrestrial spills have occurred in the oil fields but they have not been frequent or large enough for their effects to have accumulated. They have contaminated gravel, which has been difficult to clean up and has made the gravel unavailable for rehabilitation. The threat of a large oil spill—especially offshore—is a major concern among North Slope residents. This continuing concern is an accumulating effect. The effects of a large oil spill at sea, especially in broken ice, would likely be substantial and accumulate because of the fluid environment and the inadequacy of current methods to remove more than a small fraction of an ocean spill.

ABANDONED INFRASTRUCTURE AND UNRESTORED LANDSCAPES

The oil industry and regulatory agencies have made dramatic progress in slowing the accumulation of effects of gravel fill by reducing the size of the footprint required for many types of facilities and by substituting ice for gravel in some roads and pads. They also have directed some attention to rehabilitating or restoring already-disturbed sites. Despite this, only about 1% of the habitat affected by gravel fill on the North Slope has been restored. Other than for well-plugging and abandonment procedures, state, federal, and local agencies have largely deferred decisions about the nature and extent of restoration. The lack of clear performance criteria, standards, and monitoring methods at the state and federal level to govern the extent and timing of restoration has hampered progress in restoring disturbed sites. If restoration would make potential future use of a site more expensive or perhaps impossible, restoration is likely to be deferred. In addition, because so much gravel has been contaminated by petroleum spills, its re-use and the restoration of pads and roads could be constrained because of the added difficulty of restoring contaminated sites. There also is potential liability that constitutes a barrier to re-use of contaminated gravel.

Surface structures pose problems, but there also are portions of the Trans Alaska Pipeline that are buried. The pipeline connecting Alpine to Prudhoe Bay runs under the Colville River. The vulnerability of those buried pipes to shifting river channels and their removal after production ceases could pose serious problems.

By the time restoration becomes more practical because better methods are available and because the operational value of the sites has diminished, the revenue flow from oil and gas also will have declined. The large, well capitalized multinational oil companies are likely to have sold off substantial parts of their operations to smaller companies with more limited resources. Because the obligation to restore abandoned sites is unclear, and because the costs to restore abandoned sites are likely to be very high, the committee judges it unlikely that most disturbed habitat on the North Slope will ever be restored. Natural recovery in the Arctic is very slow, because of the cold; so the effects of abandoned structures and unrestored landscapes could persist for centuries and accumulate with effects of new structures.

RESPONSE OF NORTH SLOPE CULTURES TO DECLINING REVENUES

The standard of living of North Slope communities depends largely on a steady flow of money related to oil and gas activities. This way of life will be impossible to maintain unless significant revenues continue to come into those communities from outside; the prospects of other sources of revenue appear to be modest. Painful adjustments can and probably will be postponed for as long as oil and gas are being extracted, but eventual adjustment is unavoidable. The nature and extent of these adjustments will be determined by the adaptations North Slope societies have made to the cash economy made possible by oil and gas and other activities.

TRADE-OFFS ARE INEVITABLE

Continued expansion will exacerbate existing effects and create new ones. Whether the benefits derived from oil and gas activities justify acceptance of the foreseeable and undesirable cumulative effects is an issue for society as a whole to debate and judge. However, if informed decisions are to be made, the nature and extent of possible effects must be fully acknowledged and incorporated into regulatory strategies and decision-making processes. We hope this report will assist this process.

Appendix A:

Acknowledgments

The following is a list of speakers at the committee's public meetings and contributors of information.

1st Meeting, January 8-10, 2001, Anchorage, AK
George N. Ahmaogak, Sr., Mayor of the North Slope Borough
Maggie Ahmaogak, Alaska Eskimo Whaling Commission
David Allen, Fish and Wildlife Service
Art Banet, Bureau of Land Management
Lucy Beach, Gwich'in Steering Committee
Max Brewer, USGS (retired)
Sara Chapell, Sierra Club
Marcia Combes, Environmental Protection Agency
Pat Galvin, Office of the Governor of Alaska
John Goll, Minerals Management Service
Jeanne Hanson, National Marine Fisheries Service
Taqulik Hepa, North Slope Borough
Mike Joyce, Independent Consultant
Jay McKendrick, Lazy Mountain Research
Rosa Meehan, Fish and Wildlife Service
Pamela A. Miller, Arctic Connections
Gordon Nelson, USGS
Russ Oates, Fish and Wildlife Service
Walter Parker, U.S. Arctic Research Commission
Dan Ritzman, Greenpeace
Ted Rockwell, Environmental Protection Agency
John Schoen, Audubon Alaska
Stanley Senner, Audubon Alaska
Brad Smith, National Marine Fisheries Service
Pat Sousa, Fish and Wildlife Service
Bill Streever, BP Exploration (Alaska) Inc.
Steve Taylor, BP Exploration (Alaska) Inc.
Peter Van Tuyn, Trustees for Alaska

2nd Meeting, April 2-5, 2001, Fairbanks, Barrow, and Nuiqsut, Alaska

George N. Ahmaogak, Sr., Mayor of the North Slope Borough
Maggie Ahmaogak, Alaska Eskimo Whaling Commission
Rosemary Ahtuangaruak, City of Nuiqsut
Kelly Aikins, North Slope Borough
Freddie Aishamma, Whaler
Herman Aishamma, Whaling Captain
Isaac Akootchook, President of the Native Village of Kaktovik
Susie Akootchook, Secretary/Treasurer of the Native Village of Kaktovik
Charlie Brower, Whaling Captain
Eugene Brower, Fire Department, North Slope Borough
Mike Denega, Private Citizen
Nick Dunbar, Ilisagvik College
Charlie Edwardson
Gary Gortz, Ilisagvik College
David Hobbie, U.S. Army Corps of Engineers
Bud Kanayurak, North Slope Borough
John Kelley, University of Alaska Fairbanks
Lenny Landis, Ilisagvik College
David McGuire, University of Alaska Fairbanks
Deb Moore, Northern Alaska Environmental Center
Fenton Rexford, Kaktovik Inupiat Corporation
Marie Rexford
Pat Sousa, Fish and Wildlife Service
Bill Streever, BP Exploration (Alaska) Inc.
Gunter Weller, University of Alaska Fairbanks
Nancy Welsh, Alaska Department of Natural Resources

3rd Meeting, July 9-14, 2001, Deadhorse, Alpine, Arctic Village, and Fairbanks, Alaska

Ken Boyd, Alaska Department of Natural Resources
Sarah James, Gwich'in Steering Committee
Janet Jorgenson, Fish and Wildlife Service
Mike Joyce, Independent Consultant
Roger Kaye, Fish and Wildlife Service
Ryan Lance, Phillips Alaska
Fran Mauer, Fish and Wildlife Service
Jay McKendrick, Lazy Mountain Research
Dan Payer, Fish and Wildlife Service
Evon Peter, Chief of Arctic Village
John Richardson, LGL, Ltd.
Matt Rader, Alaska Department of Natural Resources
Pat Sousa, Fish and Wildlife Service
Bill Streever, BP Exploration (Alaska) Inc.
Steve Taylor, BP Exploration (Alaska) Inc.

4th Meeting, September 6-9, 2001, Fairbanks and Kaktovik, Alaska
Rosemary Ahtuangaruak, City of Nuiqsut
Paul Assendorf, General Accounting Office
William G. Britt, Jr., Gas Pipeline Office
Marilyn Crockett, Alaska Oil & Gas Association
Charlie Curtis, NANA Development Corporation
Charlie Edwardson
David C. Koester, University of Alaska Fairbanks
Jeff Mach, Alaska Department of Environmental Conservation
Joe Mathis, Alaska Support Industry Alliance
Daniel Maxim, Everest Consulting
Colleen McCarthy, Joint Pipeline Office
Debbie Miller
Pamela A. Miller, Arctic Connections
Deb Moore, Northern Alaska Environmental Center
Robin Renfroe, Doyon
Ted Rockwell, Environmental Protection Agency
Stanley Senner, Audubon Alaska
Bill Streever, BP Exploration (Alaska) Inc.
Steve Taylor, BP Exploration (Alaska) Inc.
Nancy Wainwright
Nancy Welch, Alaska Department of Natural Resources

Additional Help
Alaska Native Science Commission
Terry Carpenter, Corps of Engineers
Thor Cutler, Environmental Protection Agency
Glenn Gray, Division of Governmental Coordination
Leon Lynch, Alaska Department of Natural Resources
Dan Maxim, Everest Consulting
Ron Niebo, Everest Consulting
Rex Okakok, North Slope Borough
Evon Peter, Chief of Arctic Village
Judd Peterson, Coordinator, Alaska Department of Environmental Conservation
Gerald Shearer, MMS
Lon Sonsalla, Mayor of Kaktovik
Jeffrey Walker, MMS
Bill Wilson, LGL
Mike Worley, BLM

Appendix B:

Abbreviations and Acronyms

ABSRB: Alaska Beaufort Sea Response Body
ADEC: Alaska Department of Environmental Conservation
ADF&G: Alaska Department of Fish and Game
ADGGS: Alaska Division of Geological and Geophysical Surveys
ADNR: Alaska Department of Natural Resources
AEWC: Alaska Eskimo Whaling Commission
ANCSA: Alaska Native Claims and Settlement Act
ANILCA: Alaska National Interest Lands Conservation Act
ANWR: Arctic National Wildlife Refuge
AOGA: Alaska Oil and Gas Association
AOGCC: Alaska Oil and Gas Conservation Commission
API: American Petroleum Institute
ASRC: Arctic Slope Regional Corporation
ATV: all terrain vehicle
bbl: barrels
BCFG: billion cubic feet of gas
BEST: Board on Environmental Studies and Toxicology
BLM: Bureau of Land Management
CAH: Central Arctic Herd
CBM: coal bed methane
CEQ: Council on Environmental Quality
CFR: Code of Federal Regulations
CIA: cumulative impact assessment
CPF: central processing facilities
CPUE: catch per-unit-effort
DEIS: draft environmental impact statement
DEW: Distant Early Warning
DOE: U.S. Department of Energy
DOI: U.S. Department of Interior
DPF: Division of Parks and Forestry
DRR: dismantlement, removal and restoration
EIA: Energy Information Administration
EIS: environmental impact statement
EOR: enhanced oil recovery
ERR: economically recoverable reserves

FEIS: Final Environmental Impact Statement
FLIR: Forward Looking Infrared Sensor System
GAO: U.S. General Accounting Office
GIS: geographic information system
HDD: horizontal directional drilling
IAI: Inter-American Institute for Global Change Research
IAP: integrated activity plan
IRS: U.S. Internal Revenue Service
ITEX : International Tundra Experiment
IWC: International Whaling Commission
KDA: Kuparuk Development Area
KIC: Kaktovik Inupiat Corporation
LADS: Light Automated Drilling System
LEOS: Leak Detection Location System
LTER: Long Term Ecological Research Program (NSF)
MMPA: Marine Mammal Protection Act
MMS: Minerals Management Service
MOA: memorandum of agreement
MWD: measurement while drilling
NAAQS: National Ambient Air Quality Standards
NARL: Naval Arctic Research Laboratory
NCP: net calf production
NEP: net ecosystem production
NEPA: National Environmental Policy Act of 1969
NMFS: National Marine Fisheries Service
NOAA: National Oceanic and Atmospheric Administration
NPDES: National Pollution Discharge Elimination System
NPP: net primary production
NPR-4: Naval Petroleum Reserve No. 4
NPR-A: National Petroleum Reserve-Alaska
NRC: National Research Council
NRDC: Natural Resource Defense Council
NSB: North Slope Borough
NSF: National Science Foundation
NWPS: National Wilderness Preservation System
OCS: Outer Continental Shelf
OCSEAP: Outer Continental Shelf Environmental Assessment Program
ONR: Office of Naval Research
OOIP: original oil in place
OPEC: Organization of the Petroleum Exporting Countries
PBOC: Prudhoe Bay Oilfield Complex
PBU: Prudhoe Bay Unit
PCH: Porcupine Caribou Herd
PR: partition rate
PRB: Polar Research Board
psi: pounds per square inch

RCRA: Resource Conservation and Recovery Act
RMOL: Realistic Maximum Response Operational Limits
SAC: Science Advisory Committee
SOP: standard operation procedure
STP: seawater treatment plant
TAPS: Trans Alaska Pipeline System
TCFG: trillion cubic feet of gas
TDS: total dissolved solids
TLH: Teshekpuk Lake Herd
TPH: total petroleum hydrocarbons
TRR: technically recoverable reserves
TVD: true vertical depth
UIC: Ukpeagvik Inupiat Corporation
UNEP: United Nations Environment Programme
USACE: United States Army Corps of Engineers
USC: United States Code
USDW: Underground Source of Drinking Water
USEPA: United States Environmental Protection Agency
USFWS: United States Fish and Wildlife Service
USGS: United States Geological Survey
VSR: volumetric spill rate
WAH: Western Arctic Herd
WSA: The Wilderness Act

Appendix C:

Petroleum Exploration and Development

PETROLEUM EXPLORATION AND DEVELOPMENT ON THE NORTH SLOPE OF ALASKA

Oil Seepages, First Indication of Significant Petroleum Deposits

The first evidence of potentially significant petroleum deposits on the North Slope of Alaska came from the oil seepages that can be seen today along the Arctic Coast from Skull Cliff on the Chukchi Sea to Brownlow Point on the Beaufort Sea. Especially notable are the active ponds of oil and layers of tar at Cape Simpson just east of Barrow. It can be assumed that the native inhabitants knew of these deposits long before recorded history. John Murdoch, a member of the U.S. Navy's International Polar Expedition to Point Barrow and vicinity (1881-1883), reported in 1892 that they had heard stories of a lake of tar on an island a days sail east of Point Barrow (Murdoch 1892). This undoubtedly referred to Cape Simpson. The first non-native to see the Cape Simpson seepages may have been Charles Brower and his partner Patrick Grey while on a hunting trip in August 1886 (Brower 1942). In 1922, while on a trip to San Francisco Brower described the site to the Chief Geologist of the Standard Oil Company of California and this resulted in sending a geologic party to investigate the report (G. Dallas Hanna, unpublished report). In 1917, A. M. (Sandy) Smith, prospector, examined the oil seepages along the coast and he also stimulated the interest of the oil industry. A description of the deposits at Cape Simpson was first published by Brooks in 1909 and was based on information and materials collected by E. de K. Leffingwell. Leffingwell published more details, including chemical analyses of the oil in U.S. Geological Survey (USGS) Professional Paper 109, in 1919.

William Van Valin, a U.S. Bureau of Education teacher at Wainwright, had heard stories of an oil lake on the Arctic coast and in the summer of 1914 he traveled to Cape Simpson and staked a claim for a prospecting permit under the old mining laws (Van Valin 1941). He named the claims, the Arctic Rim Mineral Oil Claims. In 1921 several claims were staked, under the old mining laws, in areas near Cape Simpson, Peard Bay, and along the Meade, Kukpowruk, and Kokolik Rivers, by individuals and industry representatives. However, by 1921, large deposits of oil had been discovered and were being developed in Oklahoma and Texas and industry lost interest in the remote Arctic.

Widespread Oil Seepages on North Slope Confirmed in 1943

In response to inquiries by the Alaska Defence Command and officials of the Territory of Alaska, the Bureau of Mines sent a field party to the North Slope in 1943, specifically to investigate oil and gas seepages. The party was transported by float plane, piloted by pioneer bush pilot, Sig Wien, and guided by Simon Paneak, a native from Chandler Lake. They examined and sampled the Cape Simpson seepages and located several additional sites that had been rumored to occur along the Arctic Coast. Reports of seepages along the coast at Skull Cliff, Dease Inlet, Cape Simpson, Fish Creek, Brownlow Point, Manning Point, and Umiat Mountain were confirmed. Samples were collected from 12 separate sites. The descriptions of the seepages and laboratory analyses were published by N.J. Ebbley in 1944 as War Minerals Report 258.

Native Use of Petroleum Resources

The first utilization of North Slope petroleum resources was undoubtedly by the native inhabitants, the Inupiat. To what extent the natives mined and burned oil tars or pitch from Cape Simpson was investigated by G. Dallas Hanna in 1957. Several older natives at Barrow village described to him how they mined the pitch at Cape Simpson in the spring of the year and transported it in 100 lb (45 kg) sacks to Barrow by dog sled and boat. Recollections differed as to when and who began using this material. Hanna notes that in Van Valin's book, "Eskimo land Speaks", he records his sending natives to Cape Simpson for a supply of tar during a fuel shortage in 1918. Ebbley also reported seeing several sacks of pitch at the abandoned Brower Reindeer Station on Dease Inlet in 1943, a further confirmation of the early use of these petroleum resources by the local inhabitants.

Oil Shale Collected on the North Slope in 1886

The presence of oil shale was further evidence of the potential of the North Slope as a significant oil province. In 1886, Ens.W. L. Howard crossed the Brooks Range descending on to the North Slope along the Etivuluk River were he collected an unusual pebble, later identified as oil shale. Howard continued on to Point Barrow and completed what was the first recorded inland crossing of the Brooks Range and North Slope (Smith and Mertie 1930). In 1945, Simon Paneak, led a USGS field party to an exposure of oil shale on the Kiruktagiak River in the central Brooks Range. Simon said that the inland natives occasionally collected and burned oil shale and coal. Exposures of oil shale have been mapped and collected at several localities in the southern foothills of the North Slope.

North Slope Indicated as a Potential Petroleum Province in Published Descriptions of Oil Seepages and Systematic Geologic Reports, Before 1920

By 1920, published descriptions of the oil seepages along the Arctic Coast and of the geography and geology of Alaska's North Slope had indicated the region as a potential petroleum province. The first recorded systematic geologic and geographic traverse to cross the Brooks

Range and the North Slope by way of the John, Anaktuvuk and Colville Rivers was made by Peters (topographer) and Schrader (geologist) in 1901 and was published in 1904. Travel was by dog team, canoe, and umiak, native skin-boat. Schrader named and described the Lisburne Formation of Mississippian age and he named and described in some detail the Cretaceous rocks and noted the broad anticlinal structures in the foothills. Numerous coal seams were noted and described along the Colville and Anaktuvuk Rivers. They also traversed the Arctic coast from the mouth of the Colville River to Barrow and on to Cape Lisburne. Schrader describes in some detail the coal exposures along the northwest coast that had been mined by natives and whalers for many years.

From 1906 to 1914, E. deK. Leffingwell mapped the Arctic Coast east of Barrow and traversed inland over much of what is now the Arctic National Wildlife Refuge. His report was published in 1919 as USGS Professional Paper 109. Leffingwell described and named the rock formations that were to be discovered as the oil-bearing rocks at Prudhoe Bay. He noted the seepages at Cape Simpson and secured a sample "from a keg of the material collected by natives in the employment of Mr. C.D. Brower, of Barrow." He wrote of other reported seepages along the coast. He concluded that, "Even if an oil pool were found in this northern region, there is serious doubt of its availability under present conditions, though it might be regarded as a part of the ultimate oil reserves that would some time be developed." His description of permafrost and discussion of its origin on the North Slope is one of the first and a classic reference on this important subject.

1923, Naval Petroleum Reserve No. 4, NPR-4 Established

In about 1920, ships of the U.S. Navy were converting from coal to oil to fuel their engines and "experts" were already predicting an oil shortage within a few years. To provide for the future fuel needs of the U. S. Navy, Naval Petroleum Reserve No. 4 (NPR-4) was established by President Warren G. Harding, Executive Order, No. 3797-A, dated Feb. 27, 1923. The presence of major oil seepages at Cape Simpson, Ens. Howard's traverse along the Etivuluk River and across the North Slope to Barrow, the pioneering traverse and report by Schrader, and Leffingwell's classic work were major considerations in defining the borders of NPR-4.

1923 to 1926, First Detailed Geographic and Geologic Mapping of NPR-4

In 1923, the geography and geology of the interior areas of NPR-4 were largely unknown. The U.S. Navy recognized immediately that administration of the reserve would require mapping and more information on these subjects. The USGS was asked to examine and map the reserved tract. From 1923 through 1926, seven USGS parties crossed the Brooks Range and NPR-4 and mapped, at reconnaissance scales, the geology and geography along many of the larger rivers including the Kuk and Utukok in the west and the Etivuluk, Ikpikpuk, Killik and Colville in the east. Travel was by dog team, canoe and by foot. The results of the 1923-26 geologic field work were published by Smith and Mertie in USGS Bulletin 815 in 1930.

In addition to mapping the courses of the major rivers and describing the rock units and structure of NPR-4, Smith and Mertie also analyzed the petroleum potential of the reserve. Although they had very little stratigraphic information on the apparently widespread oil shales, they felt that these were the best possible sources of petroleum. They felt that sources of oil in the

Paleozoic rocks were "extremely problematic" and they recognized no abundant source rock in the Cretaceous. They noted the widespread anticlinal structures in Cretaceous rocks but thought that deposits in these rocks were "likely to be small and of extremely sparse distribution."

They recognized and described the faulted and overthrust structure of the Brooks Range but concluded that north of the range the major structure was a regional dip to the north. Thus they felt that at Cape Simpson, 10,000 to 15,000 ft (3,000 to 4,600 m) of Cretaceous was present and that older rocks were beyond practical drillable depth. Smith and Mertie cautioned would-be prospectors against the adverse geographic factors and the consequential high costs. They recommended that the next step in evaluating the petroleum resources of the reserve should be drilling for stratigraphic and structural information in the vicinity of Cape Simpson followed by geologic field studies and then drilling in other areas that appeared favorable.

1944, First Oil Exploration on Alaska's North Slope Began in NPR-4, a WW-II Project

One of the geologists in the 1923-26, USGS, NPR-4 field survey program was William T. Foran. As Lt. Foran in the U.S. Naval Reserves, he was assigned to the Naval Petroleum Reserves Office. He prepared an issue paper on the promising prospects of the NPR-4 and was largely responsible for convincing the U.S. Navy to start a petroleum exploration program in1944, commonly referred to as the Pet-4 program. It was part of the WW-II war effort and the defense of Alaska. Also in recognition of the tightening oil supplies, caused by the war, the Secretary of the Interior issued Public Land Order 82 in January 1943, which withdrew from entry, subject to preexisting rights, for use in the prosecution of the war, all the generally recognized possible petroliferous areas of Alaska including all of Alaska north of the drainage divide of the Brooks Range. This enabled the Pet-4 project, with the consent of Congress, to extend and follow discoveries and favorable trends outside of the boundaries of NPR-4. This Order was not rescinded until 1958 when Alaska became a State.

An earlier war project to supply fuel to Alaska had been initiated just across the border in Canada were oil had been discovered and a small refinery was built in 1920-21 at Norman Wells in the Mackenzie Valley just south of the Arctic Circle. The Canol project, to develop the Norman Wells Oil Field and lay a refined products pipeline to interior Alaska, was approved in February 1942. Sixty-seven wells were drilled by March 1945 and crude oil was delivered to a newly built refinery at Whitehorse, Canada, on April, 1944. The Canol project was abandoned after only one year of operation and the pipeline to Whitehorse was dismantled. The pipeline to Alaska was shut down in 1945 before any refined products were delivered. Construction of the Alcan Highway to Alaska, another war project, also started in 1942.

The wartime urgency of these projects carried over to the Pet-4 program. The initial plan for Pet-4 was to barge drill rigs from Norman Wells down the MacKenzie River and then west to Point Barrow. However, available rigs were located in Oklahoma and that plan was cancelled. But much was learned about construction and oil development in the Arctic by the Norman Wells project and this was passed on to the Pet-4 program.

The first supplies for the Pet-4 program were hauled to the Arctic in 1944 by ships of the U.S. Navy. The first Barrow expedition, Barex, rounded Point Barrow on August 5, 1944 and stood off Cape Simpson in the fog, rough weather and floating ice for five days. A suitable landing site could not be found at Cape Simpson and the expedition returned to the Barrow village site, where supplies were landed on a nearby beach and the Pet-4 headquarters camp was established. The course of the program and the future developments at Barrow would likely have been quite different if the landing at Cape Simpson had been carried out.

Geologic field surveys in support of the Navy's Pet-4 program were begun also in 1944 by USGS. Geologic traverses began along the Colville River and were expanded to all the major north-flowing rivers of the North Slope. The first geologic field parties traveled along the major streams by special collapsible boats, that could be flown out to the field along with supplies for the summer, in bush planes landing on snow. Virtually, every stream capable of floating a boat was traversed by 1950. In 1946 detailed structural geologic mapping was begun using military-style tracked vehicles (Weasels) for overland transportation. Weasels were used to cross the Brooks Range by four different routes, by way of the Okokmilaga River and the Hunt Fork of the John River and return to Umiat through Anaktuvuk Pass, by way of the Kiligwa River into the Noatak River Valley, and to the crest of the range at the head of the Utukok River. Helicopters were first used for geologic studies in the Brooks Range in 1950 in the Anaktuvuk Pass area.

Trimetrogon aerial photography covered all of National Petroleum Reserve-Alaska and special vertical aerial photography was flew over 70,000 mi^2 (181,000 km^2) of the reserve and adjacent areas. These photographs enabled geologist to interpret the possible geologic structure of nearly all of NPR-4. A special series of photo-geologic maps were produced by the USGS and were utilized to analyze and plan field surveys.

Geophysical studies including experimental airborne magnetometer, gravity and seismic surveys were started in 1945 and by 1952 covered a large part of the reserve. Seismic surveys, mostly reflection shooting, along 3,748 line miles covered about 67,000 mi^2 (174,000 km^2), including areas outside of the boundaries of NPR-4. Travel and housing of the geophysical crews was by tractor- sled trains and smaller tracked vehicles. Gravity-meter surveys covered about 26,000 mi^2 (67,000 km^2) and were conducted by small aircraft and small tracked vehicles. Airborne magnetometer surveys covered 75,000 mi^2 (194,000 km^2), nearly all of the coastal plain and much of the foothills of the North Slope.

The presence of the seepages at Cape Simpson and a quick reconnaissance of the Umiat Anticline by Foran in 1944 determined the first drilling locations. It was also decided that drilling should be limited to no more than 10,000 ft (3,000 m), thought to be the economic limit at that time for development in the Arctic. Supplies were sledded to Umiat in February and March of 1945 and a drilling and logistic support camp was established there. Drilling at Umiat began in 1945, but the Umiat Oil Field was not discovered until 1950. Umiat, however, became and is still an important operating base, for air transportation and geophysical and geological operations.

Thirty-one shallow core tests were drilled at Cape Simpson beginning in 1945. Oil was produced but the estimated reserves were considered to be too small to justify further development. By 1948 geophysical surveys had indicated the presence of a large basement high under the Barrow area. Drilling near the top of this high, discovered gas, but no oil and hard rock basement was penetrated at 2500 ft (760 m). The presence of this basement and further geophysical surveys delineated the so-called Barrow Arch, the north limb of the Colville Basin.

In 1949 a test well was drilled near the Fish Creek seepage and a high sulphur, heavy oil was found at about the 3000 ft (900 m). No structure was discernible and no reserve estimate was made. Geophysical exploration around the Barrow high continued and several tests were drilled on small structures around and stepping down from the high, but no significant oil shows were found.

The discovery at Umiat and the mapping of several closed anticlinal structures in and adjacent to NPR-4 indicated further potential in the northern foothills. Ten shallow test holes were drilled on six structures. One gas field and three prospective gas fields were discovered. Two closed structures were mapped by geophysical surveys in the western part of NPR-4 and test wells were drilled. The Meade test had strong gas shows but the Kaolak test was dry.

Thus in the period 1945 through 1952, 45 core tests and 36 test wells were drilled within and adjacent to NPR-4. The results included the discovery of one large oil field, Umiat, one large gas field, Gubik, one small gas field Barrow, three prospective gas fields, Meade, Square Lake, and Wolf Creek and two small oil deposits at Simpson and Fish Creek. When the Pet-4 program was recessed, unexpectedly in 1953, additional drill sites had been selected and some supplies had been delivered to a location east, of NPR-4 in the southern foothills, near the head of the Shaviovik River and another at the head of the Utukok River in the southwest corner of the reserve. Most of these supplies delivered to these locations were returned to Barrow and Umiat.

A comprehensive historical, year-by-year operational report by John Reed was published as USGS Professional Paper 301 in 1958. The 1944 to 1953, NPR-4 exploration program, utilized all of the then available tools and techniques of modern oil exploration and adapted them to Arctic conditions. These special adaptations and their results are described by Reed in some detail. Drilling activities, geophysical surveys, geologic surveys and studies and their results are also published in detail in USGS Professional Papers 302 through 305. Drilling samples and drill cores from the Pet-4 program are still available for study at the Alaska State Core Library in Eagle River, Alaska and the USGS core library in Denver.

North Slope Petroleum Exploration Activities Post Pet-4. 1953 to 1968

In addition to the continuation of USGS geologic field studies, several major oil companies made extensive geophysical and geologic studies throughout Northern Alaska. However no new test wells were drilled on the North Slope until 1963. Seven relatively shallow test wells were drilled from 1963 to 1965 just outside of NPR-4, near Umiat, presumably to explore for extensions and deposits similar to those in the Umiat and Gubik anticlines.

In 1966 ARCO drilled Susie No.1, and this was followed closely by two test wells near the Colville River delta, all east of the National Petroleum Reserve-Alaska. In 1967 ARCO began drilling a test well near Prudhoe Bay that was announced in 1968 as the discovery well of the Prudhoe Bay Oil Field, the largest in North America. This episode of exploration is covered in more detail in the section on industry oil and gas exploration.

Naval Arctic Research Laboratory and Other North Slope Activities Resulting from the PET-4 program.

Naval Arctic Research Laboratory

Equally and perhaps more significantly to the future development of the Barrow village, all the native inhabitants of the North Slope, and to the continuing exploration and development of North Slope Petroleum resources was the establishment and development of a research facility at Barrow. Research by the U.S. Navy, Bureau of Yards and Docks began in January 1947 in a facility of the Seabee (Navy Construction Battalion) detachment. In May 1947 a building program began to provide housing and laboratory facilities for the Arctic Research Laboratory(ARL) of the Office of Naval Research (ONR). In August 1947, ONR occupied these new facilities and ARL was born. The prefix Navy was added in the mid-1960s and ARL became NARL to more fully acknowledge the U.S. Navy's contribution to Arctic research. After the Pet-4 program was recessed in 1953, the entire camp facility was turned over to ONR until December 1954 when the Air Force took over the management of the base camp to support the DEW Line program. The Air Force continued to operate the base camp through a series of civilian contractors until October 1971 when the operation of the base camp was returned to the U.S. Navy. During the period 1954 to 1971, ONR managed the laboratory through a contract with the University of Alaska. That continued until 1980 when the NARL was decommissioned and the camp and all facilities were turned over to the Department of Interior. During the period 1980 to1984, the laboratory and all camp facilities were managed primarily as a base of operation for the Barrow Gas Fields by the USGS and their contractor. In 1984 NARL and the base facilities were turned over to the local native corporation, Ukpeagvik Inupiat Corporation (UIC).

In spite of all the management changes, NARL continued from 1947 to 1980 to serve as the logistic base and support for Arctic research on land, sea and air. Barrow inhabitants were employed at the laboratory and their experience and knowledge was utilized in many aspects of the operation and research. The laboratory, its facilities and personnel were available to the village when needed and this affected the economic and social life and development of the village in many ways. NARL had a long and very productive history of research and operations in the Arctic that contributed positively to the exploration and development of oil and gas resources on the North Slope.

Barrow Gas Field

The discovery of gas at Barrow in April 1949 was probably the most significant result of the Pet-4 project to the people of Barrow village. The Barrow Gas Fields established some interesting records. The South Field is the oldest *producing gas* field in Alaska and the South and East Barrow Gas Fields are the farthest north *producing* oil or gas fields in North America. The Pet-4 base camp, located, only 4 mi (6 km) from the nearest gas well, was fueled, initially, by oil brought in by barge once a year until the season of 1949-50 when the camp was completely converted to using gas.

When the Pet-4 project began in 1944, there were about 400 inhabitants in the Barrow village. The exploration activities provided employment opportunities for the local people and the population increased rapidly. The advantage of making gas available to the village was obvious, but it took permission from the Congress to extend gas supply to the Barrow village beginning in 1964. It was not until 1965 that the village was completely converted to natural gas. The U.S. Navy supplied gas at a subsidized cost and no limits were imposed on its use. The entire Barrow community became dependent on the Barrow Gas Fields for heat and power. The gas fields and all the base facilities and supplies were turned over to the North Slope Borough in 1984

1976, the Naval Petroleum Production Act and the 1974 to 1985 Exploration of the National Petroleum Reserve-Alaska

In 1974, the oil embargo and the discovery at Prudhoe Bay renewed interest in NPR-4 and the U.S. Navy began a new program of geophysical and drilling exploration along the Barrow-Prudhoe trend, the so-called Barrow Arch. From 1974 to 1976 the U.S. Navy drilled seven exploratory wells and found only residual oil in the formations that are productive at Prudhoe Bay.

In 1976 Congress passed the Naval Petroleum Production Act that transferred NPR-4 to the Department of Interior, renamed the reserve as the National Petroleum Reserve in Alaska and authorized the production for sale of crude oil from NPR Nos.1, 2 and 3. Thus the purpose of the reserves was redirected to augment domestic supplies. The Act authorized continuation of a new exploration program begun by the U.S. Navy in 1976, the further development and maintenance of the Barrow Gas Fields, and continuation of the cleanup program, begun by the U.S. Navy in 1975, at the suggestion of Interior Secretary Rogers Morton. The exploration program and the ongoing contract with Husky Oil Alaska Operations LTD. were assigned to the USGS.

The act also required a series of resource and management studies. The special studies were assigned to the Bureau of Land Management (BLM) as part of their regular responsibilities for the management and oversight of public lands.

The USGS took over the U.S. Navy's facilities at Barrow and Lonely on June 30, 1976 and continued the exploration program with the full support of Congress until 1982. Twenty-one exploratory wells were drilled, including two of the deepest holes in Alaska, to test seventeen plays based on the accumulated knowledge of the geology of the North Slope of Alaska and continuing geophysical surveys. From 1974 to 1982 the U.S. Navy and the USGS acquired about 13,200 line miles of additional seismic reflection data and all were made available to the public. Although nearly all drill tests had shows of oil and gas only one new deposit was discovered, the Walakpa Gas Field, about 20 mi (32 km) southwest of Barrow. This deposit was turned over to the North Slope Borough and has been developed for the long-term supply at Barrow.

The cleanup program, the environmental assessments, stipulations, and monitoring during the drilling program and geophysical surveys set a new standard for exploration activities on the North Slope. More than 25,000 fifty-gallon drums left behind by earlier projects were collected, crushed, and buried. More than 12,000 tons(11,000 metric tons) of debris were collected, burned, buried or hauled to disposal sites. Ice pads, airstrips and roads, including a 38 mi (61 km) ice road from the mouth of the Kikiakrorak River to the Inigok test well site, were used to minimize the impact on tundra vegetation. Three permanent gravel airstrips were built at Inigok, Lisburne and Tunalik drill sites and the airstrip at Umiat was extended and upgraded to support the Seabee test. Gravel drilling pads were leveled and most were seeded. The history, technical data, and analyses from this program were released to the public as open files and were published in USGS Professional Paper 1399, in 1988 (Gryc 1988).

Airstrips

Access to the North Slope for hunting by non-Alaska natives increased with the first federal (U.S. Navy) oil exploration program (1944-1953) and with the second federal program (1976-1983). These programs provided four permanent airstrips within the National Petroleum Reserve-Alaska that can be used by large aircraft. These airstrips are at Umiat on the Colville River, Inigok well site, about 60 mi (100 km) north of Umiat, Lisburne well site in the foothills on the southern border of the National Petroleum Reserve-Alaska and Tunalik well site on the far southwest corner of the National Petroleum Reserve-Alaska. Prior to 1944, aircraft access was available only to a few experienced bush pilots flying smaller, single-engine aircraft landing on natural airstrips such as gravel bars.

INDUSTRY OIL AND GAS EXPLORATION ON THE NORTH SLOPE OF ALASKA AND THE ADJACENT BEAUFORT SEA

After the completion of the Navy exploration program, the North Slope remained off limits to the petroleum industry until 1958 when lands were finally made available for industry evaluation by the federal government between the Canning and Colville Rivers. At the same time, the Arctic National Wildlife Refuge was set aside to protect the northeast corner of Alaska for its wildlife, wilderness, and recreational values. The following discussion is about exploration history and potential and is not an analysis of environmental consequences or of competing values for land use.

Factors Encouraging Industry Activity

While the industry had been aware of and interested in the possible potential of the North Slope, the lack of land availability, remoteness, and the cost of operating in this environment precluded industry participation. However, in the middle to late 1950s and early 1960s, a number of developments provided the impetus for the industry to commence active exploration of the North Slope.

Four factors contributed to the entry of the industry into the North Slope exploration scene: (1) encouraging regional geological studies, (2) the NPR-4 exploration program, (3) oil and gas discoveries in Cook Inlet, and (4) the end of the moratorium on land availability on the North Slope. The discovery of commercial quantities of oil and gas in Cook Inlet demonstrated that it was economically feasible to explore for, develop, and market hydrocarbons in and from Alaska. In 1957, Richfield Oil Corporation made the initial Alaskan oil discovery at Swanson River on the Kenai Peninsula. This discovery contributed significantly to Alaska statehood in 1959 and provided industry with the incentive for exploration of the other sedimentary basins in the state.

The North Slope was one of the areas of interest and was highlighted because of the previous work by USGS and the Navy's exploration program. Both of these efforts supported the premise that a significant reserve potential existed on the North Slope. However, the most important factor was the decision by the Federal government through the BLM to make lands available to the industry for leasing.

Pre-Prudhoe Bay Industry Activity

The industry exploration of the North Slope was greatly stimulated by the knowledge that land was to be made available for leasing in 1958, under basically the same conditions that existed in the Lower 48. Leasing and exploration activities are presented separately to provide a less cluttered flow of activity. It should be noted that the various activities are closely related in time and are interdependent.

Leasing

The federal government offered a total of 18,862.116 acres (7,639,157 ha) for lease in sales held in 1958, 1964, 1965, and 1966 (Jamison et al. 1980, Figure 2). Most of the offerings were to the east and southeast of NPR-4 (now National Petroleum Reserve-Alaska) and south of 70° N. latitude, but the lease sale in 1966 contained 3,022,716 acres (1,224,200 ha) to the west of NPR-4. The leases were offer as simultaneous filings and in blocks or tracts consisting of four contiguous sections (2,560 acres (1,040 ha).

Under the Statehood Act, the state of Alaska selected 1,616,745 acres (654,782 ha) across the northern tier between the Colville and Canning Rivers and subsequently offered these lands in three sales between 1964 and 1966. In 1964, the State held its first lease sale on the North Slope. The sale offered 650,000 acres (260,000 ha) in the Colville Delta area and 196 tracts totaling approximately 475,000 acres (190,000 ha) were leased. In July of 1965, the State held its second North Slope lease sale in the area that would eventually include the Prudhoe Bay field. The sale offering was 754,000 acres (305,000 ha) and 151 tracts totaling 380,000 acres (154,000 ha) were leased. Richfield-Humble acquired 28 blocks on what was to be the crest of the Prudhoe Bay field and British Petroleum acquired 32 blocks on the flanks. The State's third sale was held in January 1967, and thirteen tracts were offered and issued. Richfield-Humble acquired seven tracts that covered the remainder of crestal area of the Prudhoe Bay structure. This completed the leasing prior to the drilling of the discovery well at Prudhoe Bay.

Data Acquisition

With the opening of the North Slope to leasing, the industry began to acquire proprietary geological and geophysical data with the goal of better understanding the subsurface geology and the hydrocarbon potential of the region. These companies acquired two fundamental data sets: geological data through summer field programs and geophysical, primarily seismic, data by winter seismic operations. Jamison et al. (1980, Figure 3) provide a chart of exploration activity spanning the interval from 1958 to pipeline startup in 1978.

In 1958, Sinclair operated a three-month field program out of Umiat in preparation for the Federal Sale in September 1958. Sinclair was quickly followed by others, and an average of 5 to 7 companies were in the field during the 1959-1961 seasons. The number of companies continued to increase, and during 1962-1964 up to ten companies per year were operating geological field programs. During the following three years field programs declined markedly with only 2 to 3 companies in the field.

Sinclair and British petroleum operated the first industry program in 1962. (Because of the lack of information regarding the number of line-miles of data acquisition, the number of crew months is used as a gauge of activity.) The first seismic season consisted of 6.5 crew-months. In 1963 the total was 29.25 crew months and activity peaked in 1964 with 53.5 crew months of work. Seismic crew-months decreased to 26.75 in 1965, and there was very little seismic acquisition between 1965 and the season following the Prudhoe Bay Discovery.

Exploration Drilling

Based on leasing, geological field work, and seismic acquisition the industry began a program of exploration drilling in 1963 and eleven dry wells were drilled prior to the Prudhoe Bay State No. 1 (Alaska Oil and Gas Conservation Commission 2001). Colorado Oil and Gas Company drilled the first well the Gubik area. It and the subsequent seven wells were all drilled on leases acquired in the first round of Federal leasing and were located in the foothills within 30 mi (48 km) of either the Umiat or Gubik discoveries. The initial exploration efforts were focused in or near the areas that had shown the most promise in the Navy's exploration effort. All eight wells penetrated the Cretaceous and were dry holes.

With the failure of the drilling programs in the Umiat-Gubik area, the industry's focus shifted to the north and east. Two wells were drilled, one each by Sinclair and Union, during the 1966-1967 interval on acreage acquired in the first State sale in the Colville area. These were both drilled on the eastern flank of the well recognized Colville High and both were dry holes

During the same time frame, ARCO-Humble drilled the Susie No. 1 in the northern foothills of the Brooks Range on acreage leased in the State's second North Slope sale. This well was also a dry hole and presented AtlanticRichfield and Humble with a critical decision: either release the rig and forego further drilling or haul the rig 60 mi (100 km) to the north and drill in the Prudhoe Bay area. Ultimately, the decision was made to drill the Prudhoe Bay State No. 1.

Discovery at Prudhoe Bay and Aftermath

The proposed drilling site for the Prudhoe Bay State No. 1 well was on State of Alaska leases atop the Prudhoe Bay structure. The principal objective was the carbonate sequence of the Mississippian/Pennsylvanian Lisburne Group. Secondary objectives included Cretaceous clastic and the Permian/Triassic Sadlerochit sandstones. The carbonates were the preferred reservoir objective because of the highly indurated nature of the Cretaceous and Permian/Triassic units where see in surface exposures.

The drilling rig was hauled north during the winter and the Prudhoe Bay State No. 1 commenced drilling in April 1967. Drilling was suspended for the summer and resumed in the fall, after freeze-up. ARCO-Humble announced the discovery in January 1968. Upon completion of a confirmation well, the Sag. River State No. 1 7 mi (11 km) to the southeast, the recoverable economic reserve estimate of 9.6 billion bbl (403.2 billion gallons) of oil and 26 tcf of gas was released.

The timing of the well was fortuitous, as other exploration activities had virtually shut down at the time the Prudhoe Bay State No. 1 was drilled. In 1967, there were only three crew-months of geologic field work, no seismic programs were conducted by the industry and other than the Prudhoe Bay State No. 1 all drilling activity had ceased.

With the success at Prudhoe Bay, the State announced an additional sale in the Prudhoe Bay area for the fall of 1969. As a result of the magnitude of the discovery and the pending sale, the industry greatly increased the level of exploration activities on the North Slope. The geological and geophysical programs leaped from the 1967 levels to twelve geological crew-months and twenty-four crew-months of seismic acquisition in 1968 and then to twenty and ninety-seven crew-months respectively in 1969 (Jamison et al. 1980).

In 1969, thirty-three wells were drilled and completed (ADNR 2000). This number is three times the total of all industry wells drilled on the North Slope prior to the Prudhoe Bay discovery.

Alaska State Competitive Lease Sale No. 23 was held in September 1969. The sale offering was 179 tracts totaling 450,858 acres (182,600 ha). The acreage represented the unleased portion of the State's 1,600,000-acre (650,000 ha) allotment from the Statehood Act. High bids on 164 tracts totaled more than $900,000,000.00 with an average price per lease of $2,181.66 per acre ($5,386.81 per ha). This was to be the last sale on the North Slope for ten years (ADNR 2001a).

During the flush of activity immediately after the Prudhoe Bay discovery, several other oil accumulations were discovered. The major fields discovered in 1969 were the Kuparuk, West Sak, and Milne Point fields. These pre-dated the 1969 sale and provided the operators and their partners with additional information and encouragement for the sale.

Post-Prudhoe (1970 To The Present) Industry Activity

The focus of industry activity from 1969 to the present has been determined by land accessibility. There were no lease sales held on the North Slope or in the adjacent waters of the Beaufort Sea between 1969 and 1979. For that ten-year interval, drilling activity was confined to those areas that had been previously leased. Starting in 1979, the shallow State waters and Federal OCS areas of the Beaufort Sea were made available through a series of lease sales and additional onshore sales were held in the Colville-Canning area.

In the 1980s and again in 2000 portions of the National Petroleum Reserve-Alaska were opened to leasing by the Federal Government through the BLM. The Arctic National Wildlife Refuge has never been leased but there are Native inholdings and a land trade with Native corporations was considered in the mid-1980s. At various times the Arctic Slope Regional Corporation (ASRC) has made portions of their lands available to companies under exclusive exploration/leasing agreements.

The discussion of the post-Prudhoe activity will focus on four geographic areas that have different degrees of accessibility and economics. These are the Colville-Canning area/shallow State waters, the Beaufort Sea OCS, National Petroleum Reserve-Alaska, and the 1002 Area of the Arctic National Wildlife Refuge. The onshore areas frequently contain some combination of State/Native or federal/Native land ownership. The Chukchi Sea area to the west of the North Slope will not be included in this review.

Colville-Canning Area/Beaufort Sea State Waters

Through the 1970s the area between the Colville and Canning rivers, from the Beaufort Sea south to the Brooks Range, was the sole area of industry exploration on the North Slope. Because of limited land availability and the success at and near Prudhoe Bay, this area has been the focus of exploration activity since the discovery well was drilled in 1968. The bulk of exploration and drilling has been concentrated in the northern portion of the area, near Prudhoe Bay and east and west along the coastline, following the structural trend of the Barrow Arch. In 1979, the State of Alaska began a leasing program in the State waters of the Beaufort Sea. This acreage is generally confined to a strip 3 mi (5 km) wide seaward from the shoreline and from

Barrow to the Canadian Border. The issue of ownership becomes somewhat irregular in the vicinity of the barrier islands and major inlets.

Leasing

The ten-year leasing hiatus ended with a joint State-Federal Beaufort Sea sale in December 1979. The State offered 71 tracts (341,140 acres [138,162 ha]) and granted leases on 62 tracts (296,308 acres [120,005 ha]). This sale marked the first major venture into offshore leasing in the Arctic by either the State of the Federal governments and signaled the opening of a new, but highly sensitive and expensive, exploration province.

Between 1979 and the present, the State conducted 37 lease sales on the North Slope and the adjacent State waters of the Beaufort Sea (ADNR 2000 and 2001a). The level of leasing activity has varied greatly over this 20-year interval. The State offerings have ranged from as little as 677 acres (274 ha) (1989) to area wide sales, with several million acres available (1998, 1999, 2000, 2001 and 2002).

The total acreage leased was 7,659,536 acres (3,102,112 ha) with 25 onshore lease sales of 6,208,187 acres (2,514,316 ha) and 12 offshore lease sales of 1,451,349 acres (587,796 ha) (ADNR 2001a). (There have been additional State sales since this citation was published and those numbers are not included.) A significant portion of the total leased acreage includes leases that were acquired in earlier sales, subsequently surrendered back to the State and released in later sales. Lease acquisitions per sale have varied greatly during this timeframe. Onshore leasing has ranged from a high of 170 leases and 978,560 acres (396,317 ha) in the 2001 Foothills sale to a low of zero leases and no acreage in 1993 when 1,033,248 acres (418,465 ha) were offered. Offshore leasing has shown similar variability with a high of 162 leases and 323,835 acres (131,153 ha) (in 1997 when 365,054 acres (147,847 ha) were offered to a low of zero leases and no acreage in 1992 when 153,445 acres (62,145 ha) were available.

Much of this variability, especially the low participation in 1992 and 1993, reflects changes in the market and economic conditions rather than lack of success or dearth of ideas and opportunity. This was also a time when staffs were being reduced and acreage was being surrendered to the state as a cost saving mechanism. Currently, the State is holding an area wide lease sale each year and the participation has been high.

Data Acquisition

There was a change in the level and mode of data acquisition after the major discoveries in the Prudhoe Bay area. Following the high level of activity generated by the Prudhoe Bay discovery, geological and geophysical crew activity decreased sharply in the early 1970s and then slowly increased and stabilized by the late 1970s. Seismic activity was at a high in 1970 with 96 crew-months this decreased to 8 crew-months in 1972 and grew back to 54 crew-months in 1974 (Jamison et al. 1980).

In the late 1970s seismic activity averaged about 25 crew-months per year. Since 1980, the level of seismic acquisition has varied but probably averaged less than 20 crew-months per year. One of the major reasons for this decrease has been the departure of several companies and the merger of former competitors. This has resulted in a significant reduction in speculative and group seismic programs. Also, the existing regional seismic grid has been found to be of sufficient quality to allow companies to more finely tune their seismic acquisition and focus on specific areas. The more recent seismic acquisitions tend to be 3-D programs that provide a more detailed image of the subsurface than do the 2-D surveys. Seismic 3-D programs are too costly to be acquired on a truly regional scale and are generally limited to a maximum of 500 to 600 mi^2 (1,300 to 1,600 km^2).

Geological field activity has exhibited a similar profile. In the early 1970s, geological field programs averaged about 20 crew-months per year. By 1974, this had decreased to six crew-months and averaged 5 to 6 crew-months through the remainder of the 1970s (Jamison et al. 1980). During the 1980s and 1990s, the amount of fieldwork varied considerably but the activity never reached the levels seen in the 1960s and 1970s. Over the last decade geological activity has averaged 1 to 3 crew-months per year. This is once again due in large part to the decrease in the number of major companies actively exploring for oil on the North Slope and the data available from earlier field work.

One important aspect of the geological field activity is that, unlike seismic acquisition and exploration drilling, it frequently takes place external to the principal area of exploration interest. Much of the fieldwork was carried out in the Brooks Range to the south and in the Sadlerochit and Shublik Mountains of the Arctic National Wildlife Refuge. The work in the Arctic National Wildlife Refuge was severely curtailed by regulations in the late 1970s and 1980s. Entry into the Arctic National Wildlife Refuge (not the 1002 Area) has become possible in the last decade. Geological fieldwork that may have impact on the OCS and the Arctic National Wildlife Refuge would be included in the previously mentioned programs.

Exploration Drilling

Following the initial flurry of drilling activity associated with the Prudhoe Bay discovery, exploration drilling decreased markedly. The future of the pipeline was uncertain and no lease sales, offering additional drilling opportunities, were held between 1969 and 1979. Only 34 exploration wells were drilled in the five years (1970-1974) following the 1969 sale. This is only one more than was drilled in 1969. An additional 33 exploration wells were drilled during the 1975-1977 interval, prior to the start up of the Trans-Alaska Pipeline System (TAPS) in June 1977 (Jamison et al. 1980).

Between 1977, and the opening of the pipeline, and the end of 2000 an additional 193 wells in the Colville-Canning area and State waters of the Beaufort Sea have been classified as exploration wells by the State of Alaska (AOGCC 2001). This is an average of 8.5 wells per year and ranged from one exploration well in 1988 to 15 exploration wells in 1981. The most recent five-year span (1996-2000) has seen an average of eight exploration wells per year.

It appears that the Alaska Oil and Gas Conservation Commission (AOGCC) has been fairly liberal in its definition of an exploration well, and has apparently classified a large number of delineation wells as exploration wells. According to the AOGCC count, there have been a total of 296 exploration wells drilled on State leases on the North Slope and shallow Beaufort Sea since the State began its North Slope leasing program in 1964 (AOGCC 2001).

Currently, all exploration drilling is conducted during the winter and the drilling site is constructed atop an ice pad that melts away during the summer. Transport to and from these exploration sites is either via an ice road or by air.

Discoveries

From 1970 to the present, there have been 35 discoveries on State lands (ADNR 2001). These range from the currently uneconomic Kavik (1969) and Kemik (1972) gas fields in the east-central portion of the Colville-Canning province to large oil discoveries at Endicott (1978) and Alpine (1994). A very significant undeveloped resource is the Pt. Thomson gas and light oil field (1977). The field is located just to the west of the mouth of the Canning River and contains reserves estimated at 5 TCFG and 360 million bbl (15.1 billion gallons).

A point worth noting is that in the 2000 area wide State lease sale, one of the bidding groups acquired a very substantial tract of leases in the Kavik-Kemik area. They picked up all the leases, except those held by the discovery wells, which had been surrendered by previous leasees. The possibility of a gas pipeline from the North Slope has changed the perception of those discoveries. The winning companies are betting on gas and that the reserves are larger than previously estimated.

Twenty of the 35 discoveries are either developed and on production or currently being developed. Northstar located offshore, is an example of the latter. At least seven or eight of these discoveries are satellite fields and would not have been developed if they were not "immediately" adjacent to a large field with an existing infrastructure. Tabasco and the Midnight Sun/Sambuca fields are satellites each of which has OOIP of 30 to 70 million bbl (1.2 to 2.9 billion gallons).

Since the first commercial discovery at Prudhoe Bay in 1968, a total of 39 discoveries have been made on State leases and twenty-four, nearly all in the immediate Prudhoe-Kuparuk area, have been or are being developed. This area has been and will continue to be the primary exploration grounds until or unless large, attractive areas of the National Petroleum Reserve-Alaska and/or the Arctic National Wildlife Refuge become available for leasing.

Federal OCS, Beaufort Sea

The Beaufort OCS lands were unavailable to the petroleum industry until the joint State/Federal lease sale of 1979. This and subsequent sales provided access to waters beyond the three-mile limit, stretching from Point Barrow in the west to the Canadian border in the east.

Leasing

The Beaufort OCS has been the site of seven lease sales, commencing with the joint State/Federal sale in 1979 and continuing over a 20-year period to the most recent sale held in 1998 (ADNR 2001a, MMS 2001c). These sales were held at two to five year intervals, with sales in 1979, 1982, 1984, 1988, 1991, 1996, and 1998.

The total acreage offered was 54,811,200 acres (22,198,500 ha) in 10,131 blocks (MMS 2001c). The total includes previously unoffered lands, reofferings of surrendered leases, and reoffering of previously offered but unleased acreage.

The offerings ranged in size from 173,423 acres (70,236 ha) in 46 blocks (1979) to 18,556,776 acres (779,384,592 ha) in 3,417 blocks (1991). Issuance of leases ranged from a low of 24 blocks with 85,776 acres (34,739 ha) in 1979 to a high of 227 leases with 1,207,714 acres (489,124 ha) in 1984 (MMS 2001c). The earliest phase of leasing in the late 1970s and early 1980s drew the greatest level of interest with approximately 21 percent of the offered acreage being leased. The large acreage offerings of the late 1980s and early 1990s (7.28 to 18.56 million acres [2.9 to 7.5 million ha]) drew relatively little interest, with only 3.5 percent of the offered blocks receiving successful high bids. Interest may be on the rise once again. At the most recent sale in 1998, 9.3% of the 920,983 acres (372,998 ha) offered were leased.

Interest peaked early not only in terms of the percentage of offerings receiving bids but also in terms of the values bid on the leases. The average per block bid in the first three sales was in excess of $9,200,000. The lease sales in the late 1980s and early 1990s averaged $377,940 per block. The most recent sale averaged $222,822 per block.

These sales resulted in the issuance of 688 tracks and a total of 3,530,514 acres (1,429,858 ha) (MMS 2001c). Of the 688 tracts leased, only 82 leases or 12 percent are active today (MMS 2001c). Most of these leases are clustered around the discoveries or are associated with newly defined prospects acquired in the most recent sales.

Data Acquisition

The data acquisition issue is somewhat different in the case of the OCS regions. There is little or no geologic field work conducted exclusively for the purposes of developing a better understanding of the offshore subsurface geology. Rather, the subsurface well control from onshore drilling activities and secondarily outcrop geology is tied into the seismic grids to extend the geologic interpretations into the offshore areas and assist in the definition of potential prospects.

Seismic acquisition in the OCS is not well documented; however, commencing in the middle- to late-1970s both summer marine and winter ice programs have been acquired to correlate the better explored and understood onshore geology into the Beaufort Sea. Most, if not all, of the existing seismic data are 2-D with little if any 3-D acquisition outside of the areas of existing discoveries or prospects that are being prepared for drilling within the next few seasons. While the per season or total acquisitions are not known, the totals are easily in excess of 5,000 line-miles.

The existing seismic grid extends across state waters and ties into onshore wells or wells in the shallow near-shore portions of the Beaufort Sea. The acquisition area extends from near Point Barrow on the west to near the Canada border on the east.

Exploration Drilling

The Alaska Department of Natural Resources (ADNR), Division of Oil and Gas (2000) states that 27 exploration wells were drilled within the OCS, without providing a listing of these wells. The Minerals Management Service (MMS 2001) counts 30 exploration wells. This discrepancy is probably the result of the Division of Oil and Gas considering wells drilled on acreage jointly owned by the State and Federal governments to not be OCS wells; whereas, MMS considers these same wells to be OCS wells.

The first OCS exploration well was the Beechy point No.1, spud in 1981, and the most recent exploration well was the Warthog No. 1, spud in 1997. The peak of exploration drilling was in 1985-86 when 11 of the 30 exploration wells were drilled. A secondary drilling mode occurred in 1991-93 with 7 wells drilled. Since 1993, only two exploration wells have been drilled, and both of these were drilled in 1997 (MMS 2001). Phillips Alaska, Inc. had planned to drill an exploration well on its McCovey Prospect in 2001 but was unable to drill the well because of permitting problems. AEC Oil and Gas planned to drill this in the 2002-2003 drilling season.

Depending on water depth, the OCS exploration wells are either drilled from man-made ice islands or large, heavy, bottom-anchored, ice-resistant drilling rigs. If a discovery is made and the field developed, a more permanent structure is built to provide the base for such long-term operations.

Discoveries

Eleven of the OCS exploration wells have been determined to be capable of production (MMS 2001). Of these, five have been termed significant discoveries (MMS 2001 and ADNR 2000). Four of these are in OCS waters and are the Kuvlum, Hammerhead, Sandpiper, and Tern/Liberty. The fifth discovery is the Northstar field (Seal well) which underlies federal and state acreage. The first discovery in the OCS was Tern/Liberty in 1983. It was followed by Seal/Northstar in 1984, Hammerhead in 1985, Sandpiper in 1986, and Kuvlum in 1992.

Water depths range from as little as 21 ft (6 m) at Liberty to as much as 110 ft (34 m) at Kuvlum. These depth variations dictate both the type of basic exploration drilling structure to be used and the type of production platform to be built. The costs escalate significantly with incremental increases in water depth.

Three of these discoveries, Tern/Liberty, Sandpiper, and Northstar lie offshore from the well-established Kuparuk and Prudhoe Bay fields and their infrastructure. The Hammerhead and Kuvlum discoveries are well to the east of the Prudhoe Bay field in relatively deep water. Hammerhead is offshore from the Pt. Thomson and Flaxman discoveries. The Kuvlum discovery is to the east of the Canning River and offshore from the 1002 area of the Arctic National Wildlife Refuge.

The Northstar field has been developed and began production in late 2001. The fate of the Liberty field development is unknown at this time.

The OCS lands of the Beaufort Sea, now and in the foreseeable future, provide a modest to good potential for the discovery and development of large fields (≥500 million bbl [21 billion gallons]) and smaller satellite fields supported by these larger discoveries. The McCovey prospect is but one example of such prospects awaiting the drill. However costs, environmental issues, and the regulatory climate will delay drilling of exploration wells and the rapid development of any new discoveries. Lead-time from discovery to first production may be two-four times that of a comparable onshore field.

National Petroleum Reserve-Alaska

After the completion of the second round of federally sponsored exploration in the National Petroleum Reserve-Alaska, the government elected to open the petroleum reserve and encourage industry exploration. The second phase of federal exploration did not yield any significant discoveries but did provide a wealth of information for future operations.

Leasing

The federal leasing program in the National Petroleum Reserve-Alaska commenced in 1982 with two lease sales in January and May. A total of 271 tracts with 5,035,772 acres (2,039,488 ha) were offered in the two sales. Most of the acreage was located in the south and southeastern portions of the National Petroleum Reserve-Alaska. Between the two sales 38 tracts with a total of 927,965 acres (375,826 ha) were leased. The leased activity was focused in the areas west of Nuiqsut, west of Umiat, and west of the Lisburne well. In both sales the leasees appeared to be pursuing Umiat play-types.

A third sale was held in July 1983. This sale offered 84 tracts and 2,195,845 acres (889,317 ha) spread across the northern portion of the National Petroleum Reserve-Alaska. Twenty tracts, totaling 419,618 acres (169,945 ha), were leased (BLM 1990). These tracts appear to have been selected to evaluate Prudhoe Bay play-types and were largely concentrated in the area between Admiralty Bay and the Chukchi Sea.

A fourth sale was scheduled for July 1984. Sale No. 841 was to offer 64 tracts and 1,550,677 acres (628,024 ha). When no bids were submitted for the sale, leasing was cancelled (Weimer 1987, Banet 1991).

During this brief leasing period, the industry acquired 58 tracts and 1,347,583 acres (545,771 ha). None of these leases are currently in force. The last of these leases were relinquished in the early 1990s.

The discontinuance of leasing in 1984 resulted in a 15-year hiatus in leasing activity and exploration in the National Petroleum Reserve-Alaska. It was not until after the 1994 discovery of the Alpine field in the Colville Delta area that the government recognized the renewed industry interest in the National Petroleum Reserve-Alaska and re-instituted leasing in the petroleum reserve.

With the assistance of the MMS, the BLM developed a leasing program in the late 1990s, and the first sale of this new series was held in May 1999. The sale was restricted to the northeastern corner of the National Petroleum Reserve-Alaska, an area comprised of 4.6 million acres (1.9 million ha). The sale was conducted with multiple restrictions regarding drilling locations and presence of surface facilities. Approximately 3.9 million acres (1.6 million ha) were offered. This offering drew 132 high bids on 861,368 acres (348,854 ha). Twenty-two percent of the offered acreage was leased (BLM 2001).

The bulk of the leased acreage is in the vicinity of Nuiqsut and extends from the Colville River westward through Townships 9-12 North to Range 6 West. A second, smaller block of leased tracts lies between Teshekpuk Lake and the Ikpikpuk River (Mapmakers Alaska 2000). These leased areas include lands that were originally leased in the 1980s leasing episode, but they were surrendered without having been drilled.

The leasing pattern indicates that the industry is focused on exploring for Alpine-type plays in the area of eastward migrating Jurassic and Early Cretaceous shelf margins. Additional objectives probably resemble Tarn and Kuparuk plays.

An additional sale was held in the northeastern area in 2002. It was essentially a re-offering of 3,051,500 acres (1,235,858 ha) not leased in the 1999 sale. A total of 60 tracts with 579,269 acres (234,604 ha) were leased. The newly leased acreage is generally to the south and west of the previously acquired leases.

Data Acquisition

The bulk of the data utilized in the industry's evaluations were obtained by federal agencies during their exploration efforts. A total of 16,479 line-miles of seismic data were acquired during the government's exploration effort (Schindler 1988). These data are publicly available and have been extensively reprocessed to enhance their utility.

In the early 1980s, a number of geologic field parties were conducted in the foothills south and southwest of the the National Petroleum Reserve-Alaska, along the Colville River, and in the coastal area from the vicinity of the Corwin Bluffs to Cape Lisburne.

After the discovery of the Alpine field and in preparation for pending sales in the National Petroleum Reserve-Alaska, the major participants in ongoing North Slope exploration began to conduct 2-D and 3-D seismic programs in the probable sale area. The total line-miles of seismic data acquired are not known. There were at least seven 2-D programs acquired between 1992 and 1997 totaling 2,615 line-miles. A single 3-D program was shot in 1996 and covered an area of 152 mi^2 (394 km^2) (Kornbrath et al. 1997). There have been additional 2-D and 3-D programs acquired since 1997; however, the number of programs and coverage are not known.

Exploration Drilling

Leasing in the early 1980s resulted in the drilling of only one industry exploration well within the National Petroleum Reserve-Alaska. This was the ARCO Brontosaurus No. 1. It was drilled in 1985 as a test of the Ivishak truncation—a Prudhoe Bay style prospect. The well was located in the western portion of the National Petroleum Reserve-Alaska about 40 mi (64 km) south-southwest of Point Barrow. The hole was dry and any other plans to drill were abandoned. However, the well was not an entire waste, as it provided a much-needed data point and an additional control for future exploration in the Chukchi Sea. An additional well, the Chevron Livehorse, was drilled on Native inholdings and will be discussed later.

After Sale No. 991 in 1999, the industry commenced an extensive drilling program in the northeastern portion of the National Petroleum Reserve-Alaska. Three wells were drilled in the winter of 2000 and an additional six wells were drilled in 2001. Most, if not all, of these wells are probably targeting Alpine-style prospects. It is anticipated that drilling and additional lease sales will keep this area an active focus of exploration for at least the next six to ten years.

Discoveries

At least five of the wells drilled in the National Petroleum Reserve-Alaska have discovered hydrocarbons. Both oil and gas were found. The size of the discoveries has not been made public. But the operators have indicated that the oil reserves are at least equal to those of the Alpine field. The gas potential is unknown.

Arctic National Wildlife Refuge

The 1002 Area of the Arctic National Wildlife Refuge has long attracted the interest of the petroleum industry. There are numerous active oil seeps, exposures of oil-stained sandstone, and large attractive structures. However, these lands are currently closed to the Industry and can only be opened for exploration and potential development by an act of Congress.

Leasing

Because ANILCA prohibits it, there has been no leasing in the 1002 Area. However, in 1987 the Reagan administration proposed to trade land/exploration rights in the 1002 Area for Native corporation inholdings in National Parks and other sensitive areas. Six Native corporations were found qualified to participate and each chose an industry partner. The industry partners were to supply technical expertise and have exclusive right to explore any lands acquired by their Native corporation partners.

The federal government did propose and develop a tract selection/trade process and the Native corporations and their industry partners proceeded to bid on 71 complete or partial tracts. These tracts were 4 mi^2 (10 km^2) parcels. This land trade was never carried through to completion and the lands were not transferred. As a point of interest, virtually all the prospective trade lands identified in that process were either along the Marsh Creek Anticline or to the east of it. Unpublished industry evaluations have tended to place a greater portion of the areas potential resources in the deformed area. This would include the Marsh Creek Anticline and areas to the east.

Data Acquisition

Data acquisition in the Arctic National Wildlife Refuge has been largely restricted to geological field parties in the Brooks Range, south of the 1002 Area, and to the limited seismic acquisition program conducted under government oversight in 1984 and 1985.

The seismic program was acquired during successive two field seasons (1984 and 1985). A 22-company consortium shared the cost of the data acquisition and processing. These two seasons produced approximately 1,400 line-miles of mostly poor to moderately good data quality. Because of the paucity of seismic control, public and proprietary gravity and magnetic data were used extensively in the Arctic National Wildlife Refuge.

Exploration Drilling

Since there has been no leasing within the 1002 Area, there has been no exploration drilling. However, Kaktovik Inupiat Corporation holds surface title to some lands, and the city of Kaktovik lies within the boundaries of the refuge. British Petroleum/Chevron drilled a well on native lands through an exclusive exploration agreement with the Native corporation. The information from this well has been held confidential since it was drilled in 1986.

Discoveries

Since there has been no drilling within the 1002 Area there have been no discoveries. However, there are two discoveries west of the Canning River that abut the 1002 Area. It is possible that either the Sourdough or Pt. Thomson fields may extend eastward into the 1002 Area. If and when they are developed, they may have the potential to drain oil and/or gas from beneath the Arctic National Wildlife Refuge.

Native Corporation Lands

The Arctic Slope Regional Corporation (ASRC) and its various village corporations have extensive land holdings across the slope. These extend from Barter Island in the east to the Chukchi Sea in the west and from the Beaufort Sea in the North to the crest of the Brooks Range in the south. The regional corporation and several of the village corporations have entered into exploration agreements with various petroleum companies. These agreements have generally required some form of initial monetary commitment, specific work commitments, and an agreement to lease potential acreage or forfeit the right to explore at an agreed upon date. One or more exploratory wells are also required if the company elects to go to lease.

Leasing

There is no competitive leasing process such as the MMS or DOG utilize to make lands available to industry. The negotiations are generally confidential. Chevron, Texaco, ARCO, and Unocal have had such agreements in the past. Anadarko Petroleum and its partners currently have an exclusive exploration agreement with ASRC for nearly 3 million acres (1.2 million ha) in the Foothills area of the Brooks Range.

Data Acquisition

The data acquired on Native corporation lands, especially seismic and other geophysical data are usually kept confidential, and the data are only available to the corporation and its industry partners. Therefore, it is difficult to assess the amount and quality of such data. Geological field programs are in most cases applicable to both State and private lands and have been addressed previously. However, with the recent interest in a gas pipeline, there has been increased activity in the Brooks Range foothills, and the Native corporation lands there are being reevaluated for both oil and gas. This has resulted in a recent increase and refocus of geologic field efforts in the foothills belt. Similarly, new seismic data were acquired during the recent winter seasons. These seismic programs included both 2-D and 3-D acquisition technologies.

Exploration Drilling

Through ASRC's exploration agreements with various companies, eleven exploration wells have been drilled on Native corporation lands on the North Slope (ADNR 2001b). Some of these Native corporation holdings are in the form of inholdings within national parks, national monuments, and wildlife refuges. This has afforded those companies with Native corporation exploration agreements the opportunity to drill and evaluate areas that are not otherwise assessable and are off limits to the rest of the industry. These wells have been drilled on inholdings within the Arctic National Wildlife Refuge and the National Petroleum Reserve-Alaska as well as in the foothills of the Brooks Range south of the State acreage in the Colville-Canning area. There have also been wells drilled on ASRC lands to the west of the National Petroleum Reserve-Alaska.

A listing of these wells, their general location, year drilled and operator is presented to indicate the spectrum of ASRC holdings.

	OPERATOR & WELL	LOCATION	YEAR
1.	Texaco, Tulugak No.1	26-5S-3E (Umiat)	1977
2.	Chevron, Eagle Creek No.1	29-8S-45W (Umiat)	1978
3.	Chevron, Tiglukpuk No.1	15-12S-2E (Umiat)	1978
4.	Chevron, Akuluk No. 1	23-5S-49W (Umiat)	1981
5.	Chevron, Killik No. 1	08-12S-10W (Umiat)	1981
6.	Chevron, Cobblestone No. 1	25-10S-8E (Umiat)	1982
7.	Chevron, Livehorse No.1	13-17N-2W (Umiat)	1982
8.	Unocal, Tungak Creek No. 1	12-6N-42W (Umiat)	1982
9.	Chevron/BP, KIC No. 1	01-8N-36E (Umiat)	1986
10.	ARCO, Big Bend No. 1	24-3S-2W (Umiat)	1993
11.	ARCO, Nuiqsut No. 1	05-11N-4E (Umiat)	1998

The KIC well was drilled on Kaktovik inholdings in the Arctic National Wildlife Refuge and provided Chevron and BP with a source of information unavailable to all other companies. The well is being held confidential. The Livehorse well was drilled on native inholdings in the northern part of the National Petroleum Reserve-Alaska. It provided Chevron a data point that could have been of benefit in the sales held in the National Petroleum Reserve-Alaska during the 1980s.

The Akulik, Eagle Creek, and Tungak Creek wells are located to the west of the National Petroleum Reserve-Alaska and are the only wells in that portion of the North Slope. The information from these wells provides the only subsurface data in this part of the state. There are only two other wells, both within the National Petroleum Reserve-Alaska, within 100 mi (160 km) of these wells.

The Cobblestone, Killik, and Tiglukpuk wells are the southern-most wells on the North Slope. They are well south of the existing leased acreage of the Colville-Canning area and provide key subsurface information for the foothills lease sales, especially with regard to gas potential.

The availability of native corporation lands can provide a company with access to areas otherwise off limits to the industry and may supply data that will give the operator an advantage over competitors in future land acquisitions. Additionally, these wells may lead to large discoveries that lack the problem of joint ownership with those same potential competitors.

Discoveries

There has been one discovery associated with ASRC lands in the Colville River delta. The Alpine field extends beneath leases jointly held with the state. The KIC well has been held confidential by Chevron and BP, since it was drilled in 1986. There has been considerable discussion regarding the stratigraphic succession that may have been encountered as well as speculation regarding the presence of hydrocarbons in either commercial or sub-commercial quantities. If commercial hydrocarbons were found, there is still a major problem confronting any plans for development even if Congress allows oil and gas activity in the Arctic National Wildlife Refuge and/or the ASRC inholdings to oil and gas development and production. To produce any oil that may have been found at KIC, a pipeline to TAPS would have to either pass westward across the 1002 Area or be buried offshore in the Beaufort Sea. The offshore pipeline would need to extend westward beyond the Canning River before it could be brought ashore and tied into future pipelines in the Pt. Thomson/Sourdough area.

To date, the relative remoteness of the native land selections has required very large reserves or has encountered access barriers that have somewhat limited the general industry interest. With the development of a more far-reaching infrastructure and the pending market for natural gas, the native land position may assume a preeminence not seen before on the North Slope.

Future Exploration Potential

There has been concern regarding the long-term viability of the oil and gas industry on the North Slope. The declining production at Prudhoe Bay, Kuparuk and other older fields has led to speculation that the industry will soon turn its eyes and investments elsewhere. However, with the advances in technology, the development of new exploration concepts, and the pending market for gas should be sustained provided that the exploration opportunity exists and that lands are made available for future drilling and development. Within the geographic confines of the North Slope and Beaufort Sea, there are at least four areas of opportunity for the future exploration and development.

Continuation Of Present Exploration Trends

The Colville-Canning area and the Beaufort Sea will continue to be the central focus of exploration for some time. There is little doubt that small satellite accumulations will continue to be found in close proximity to the major facilities at the Prudhoe Bay and Kuparuk fields. However, these will fall far short of offsetting the production declines in the major fields. The major petroleum potential exists in the Federal OCS portion of the Beaufort Sea and to a lesser extent in the State waters.

The Jurassic, Cretaceous, and Early Tertiary age shelf sandstones and lower slope to basin turbidite objectives will continue to be targets and may yield additional Alpine and Point McIntyre size fields. The probability of finding large Prudhoe Bay- or Endicott-type fields in the northern portion of the Colville-Canning area or in the shallow Beaufort Sea is low.

National Petroleum Reserve-Alaska

Early exploration efforts by the Navy and USGS severely damaged the hopes of finding Prudhoe Bay and Lisburne/Endicott style plays along the westward extension of the Barrow Arch into the National Petroleum Reserve-Alaska. However, the Barrow, Simpson, and Walakpa gas fields of northwestern the National Petroleum Reserve-Alaska and the Alpine oil field of northeastern the National Petroleum Reserve-Alaska indicate that these Jurassic/Cretaceous shallow marine shelf reservoirs offer a multitude of opportunities. This trend could potentially be pursued across the entire northern half of the reserve. As seen at Alpine, there is the potential for 500 million bbl (21 billion gallons) fields.

Oil plays may extend well south into the foothills. The Navy's discovery at Umiat demonstrates the potential for reserves in the several tens to a few hundred million barrels range. Recent work by the USGS and DDGS has, shown that even in the southern portions of the National Petroleum Reserve-Alaska and at the same latitudes to the east and west, that source rocks currently in the oil window and oil stained sandstones are not uncommon.

With an ongoing leasing program in place, the National Petroleum Reserve-Alaska may play a significant role in the future viability of the North Slope as a hydrocarbon province. However, it is unlikely that the area will yield fields that will rival Prudhoe Bay or even Kuparuk in terms of recoverable reserves.

Arctic National Wildlife Refuge

The environmentally and politically sensitive 1002 Area of the Arctic National Wildlife Refuge has the greatest remaining potential for the discovery of large oil fields in Alaska. Large structures are evident on the surface and from the limited seismic data. Oil seeps occur at several localities, there are numerous exposures of oil stained sandstone, and several accumulations abut the area on the west and may possibly extend into the refuge.

Several high quality oil source rocks are known to be present within the Arctic National Wildlife Refuge. They are exposed in the front ranges to the south of the 1002 Area and within the 1002 Area itself. These sources are locally sub-mature to mature for oil generation and support the thesis that oil has been generated and may have accumulated in the large structural and stratigraphic traps of the coastal plain.

The technically recoverable reserves attributable to the 1002 Area have been estimated to be as great as 11.8 billion bbl (496 billion gallons) with a mean estimate of 7.7 billion bbl (322 billion gal) (Bird and Houseknecht 1998). There is no comparable publicly available estimate for gas reserves.

Gas Plays in the Foothills and Portions of the National Petroleum Reserve-Alaska

With the possibility of a gas pipeline to transport North Slope natural gas to domestic and world markets, there is increased interest in gas exploration. Without a gas pipeline or the promise of one, gas has had no value and in fact has had negative value in those cases where gas-handling costs are high.

In addition to the major gas reserves associated with the large oil fields along the Barrow Arch, there have been several minor gas discoveries in the Brooks Range Foothills. The best known discoveries are Gubik, Kavik, and Kemik gas fields. The Gubik gas field was discovered during the Navy's National Petroleum Reserve-Alaska exploration program in 1951, and the Kavik and Kemik fields were discovered by the industry in 1969 and 1972 respectively. Each of these fields is estimated to contain 100 to 300 or 400 BCFG.

The southern area has large structures, abundant gas-prone source rocks or overmature oil-prone source rocks, and thick sequences of sandstone with porosities and permeabilities adequate for gas reservoirs. Fracturing tends to be common and is the source of the bulk of the porosity in the Kavik and Kemik wells.

The emerging gas potential of this area can be seen in the bidding trends of the State's 2000 and 2001 North Slope and Foothills area wide lease sales. This strongly implies a very concerted effort to explore the area for gas as well as the more conventional oil plays. This area has the potential to equal the reserve base of the Barrow Arch-associated gas accumulations and would signify a long-term future for gas exploration and production on the North Slope. A gas pipeline along the haul road from Prudhoe Bay would pass through the central portion of this potential gas province. Spur pipelines to the east and west could be constructed to tie into the gas line in the vicinity of TAPS pump station No. 3.

Factors Influencing Future Exploration

The North Slope may continue to play a major role in meeting the energy requirements of the United States well into the twenty-first century, but several key elements will greatly influence the magnitude, stability, and duration of that role. Among the most significant of these factors are oil and gas prices, land availability, regulatory environment, and level of competition.

Prices

The price structure for oil, and to a lesser extent gas, and its stability will play a pivotal role in the future of the petroleum industry in Alaska. Recent low world oil prices have demonstrated just how sensitive the Alaskan oil industry is to fluctuations in price. With low prices, the high cost of producing a barrel of oil in Alaska places North Slope crude at a disadvantage relative to the OPEC cartel and other low-cost producers. It also tends to dry up funding for Alaskan projects by the producing companies who can realize a greater return on investments in those same low-cost environments. With prices that provide a reasonable return on investment, exploration and development opportunities will continue to attract industry to the North Slope.

Land Availability

Even with sustained high oil prices, there will be no significant reserve additions without attractive exploration opportunities. These opportunities only exist when there is a continued and diverse offering of exploration acreage. A successful exploration effort requires that a broad mixture of potential play types of a size sufficient to provide economically viable targets be made available in a predictable and systematic manner. In such a scenario, exploration would provide a spectrum of field sizes such that the larger accumulations generate the demand for the infrastructure, which will in turn create an environment in which smaller fields (satellites) may be profitable to develop.

In the relatively near future, the available relatively low-cost operating areas, near existing infrastructure will have been reasonably well explored. They will be deemed to no longer have the potential to yield discoveries of sufficient size to replace the production lost due to decline of the older major fields. At that point, there will either be pressure to open additional lands to exploration or it will be acknowledged that the region is in decline and that reduced production will ensue and eventually lead to the shutdown of operations and the pipeline.

Prediction Versus Reality

Apparent failure of early stage predictions, regarding reserve size, number of wells to be drilled, size of areas to be affected by development, and miles of roads and pipelines, has caused concern and raised the issue of credibility in some minds. Obviously, if anticipated potential effects are based on the early stage predictions any significant deviation from those forecasts will result in a difference in the magnitude of any activity-associated effects.

The problem lies in the failure to recognize that each of these predictions, whether they are the number of oil fields in an area, the size of the accumulations, or the amount of infrastructure necessary, is based on very little solid scientific data. When exploration begins in a new area, like the North Slope in the 1960s, no one has direct evidence of the true nature and distribution of potential reservoirs in the subsurface, let alone the presence or volume of hydrocarbons that may be present. Seismic data used to determine the presence of potential structures and traps, and outcrop exposures, often tens or hundreds of miles away, are the sole source of possible reservoir data. Based on these bits of information a first prediction is made as to the probability of oil or gas being present, and then if the assumptions regarding structure, trap, reservoir, and source are reasonable, what range of hydrocarbon volumes may the feature contain? As can be readily seen, the reality as revealed by the drill may be very different from the pre-drill predictions.

Prudhoe Bay was a definite surprise, it was far larger than expected and the vast bulk of the oil was found to be in a rock that was not thought to be a reservoir target prior to drilling the well. The first predictions were wrong. The second prediction at Prudhoe Bay was that the field contained 9.6 billion bbl (403.2 billion gallons) of recoverable oil. An independent company based on the evaluation of delineation wells determined this value. Subsequent planning for the field used that reserve figure. Advances in technology, and geologic variability in the reservoir have placed current estimates of recoverable oil in the 13 billion bbl (546 billion gallons) range.

Similar results have been noted at Kuparuk and Endicott fields. The Lisburne field has not met expectations either in terms of daily production rates or cumulative production. This is largely the result of applying the incorrect reservoir model to the field in its early stages.

Predictions made at the time of the discovery of these fields did not recognize the upside that existed (or the downside in the case of the Lisburne). As a result estimates of the life span of the fields, size of areas to be affected, number of wells to be drilled, and other variables were not precise and should not have been expected to be.

Additionally, the development of the infrastructure at Prudhoe Bay and Kuparuk, plus TAPS made exploration for previously unrecognized or ignored nearby small accumulations feasible. This again contributed to a larger area of development than was forecast at the time of the original estimates. Once again is must be recognized that these satellite fields were either unknown, not economic under then present economics, or were known to individual companies as a result of proprietary data which were not shared with competitors for obvious reasons.

These early estimates work both ways, there tend to be more over-estimates of potential than under-estimates. The public generally never hears of these because the either the company drills a dry hole and abandons the project or it acquires additional data that indicates the prospect is invalid or uneconomic and no drilling occurs. The most notable failure in north Alaska was the Mukluk well. The potential of this prospect was thought by many to rival Prudhoe Bay. Exploration, leasing, and drilling costs may have totaled as much as $2 billion. The well was drilled and abandoned as a dry hole.

Uncertainty and risk are the nature of the exploration business. Any company that is willing to spend the money and time to acquire data, lease land, and drill exploration wells is hoping for a discovery of a size sufficient to justify the costs and provide an adequate, competitive return on the investment. That company is also gambling that the field will provide the infrastructure to support possible nearby accumulations when and if they are found.

An observer may note that when an exploration company acquires a new lease or block of leases, it will often permit multiple well locations. In reality, only a fraction of these locations are normally drilled. This is due either to a failure to discover an economic accumulation in the most favored locales or because the initial interpretation of the geology was not correct.

Historically the successful prediction of exploration and development activity in terms of how much, when, and where has been as much an art as it is a science. Recent technological advances have resulted in a much improved exploration success rate, but frontiers areas still bear a high risk and failure rate. With the full awareness of this uncertainty, a range of potential and cumulative effects of future oil and gas activities can be addressed. The best approach is to use the knowledge derived from known activity and its effects and project a likely case into the future, with a series of scenarios that vary the future activity within reasonably constrained limits. This approach still will not guarantee when, where, and how much. However, it should provide the most reasonable range of estimates of the overall effects of future activities.

Appendix D:

Oil Field Technology and the Environment

TECHNOLOGY IN EXPLORATION

Advances in exploration-related technology have been directed toward more precisely identifying subsurface drilling targets in order to reduce the number and cost of exploration wells (DOE 1999) and to reduce the impact on the physical/biological environment. Technologies such as 3-D seismic-data acquisition and 4-D visualization allow for the drilling of fewer wells and the use of ice roads and ice pads, plus remote sensing, can decrease the direct impact on the tundra, although the long-term effects are not fully known. These newer technologies have largely replaced the older, less-efficient and, in some cases, less environmentally friendly practices and techniques.

3-D Seismic-Data Acquisition/4-D Visualization

Improvements in 3-D seismic-data acquisition and other exploration technologies allow geologists to identify higher quality prospects and to improve success rates by as much as 50 percent or more. In 1970, the success rate for exploration wells in the U.S. was about 17 percent. In addition to the advances in data quality and acquisition procedures, there have been important advances in the engineering of the vehicles used to move the camp equipment and to acquire the data. The major changes have been in the development of new "light-weight" rubber tracked caterpillar-type vehicles and vibrators, that do less damage to the tundra and willows than the older vintage steel-tired vehicles. With the use of 3-D seismic-data acquisition, success rate had increased to 48 percent in 1997 (DOE 1999, Revkin 2001). Phillips Alaska, Inc. and Anadarko Petroleum Corporation's recent exploration success in the National Petroleum Reserve-Alaska was an astonishing five successful wells of six drilled (Petroleum News Alaska 2001).

About 25 years ago, 3-D seismic technology was introduced. Data are acquired in a grid-like manner with the individual lines spaced only a few hundred feet apart, and are computer manipulated to create multidimensional representations of the subsurface. The result is a far better understanding of the geologic structures and continuity of the potential hydrocarbon-bearing formations. As with the older generation 2-D seismic data, onshore 3-D seismic data are acquired during winter, after freeze-up to a depth of 12 in. (30 cm) and an accumulation of 6 in (15 cm) or more snow. Vibrators are used and these energy sources and the crews, camps, and other support facilities are carried on and/or are usually towed by low-impact tundra travel vehicles (Lance 2000). Seismic grids may cover an area of hundreds of square kilometers. Most offshore 2-D and 3-D seismic data are acquired during the open water season using airguns rather than vibrators. Some offshore data, in the area of bottom-fast ice, are acquired during winter using land technology. The 3-D data sets are often used throughout the life of a field to plan infill and injection wells.

The older land-based 2-D seismic technology consisted of long, intersecting seismic lines that used either dynamite or vibrators as the energy source. In the early stages of acquisition on the North Slope, much less care was taken to protect the tundra from damage during data acquisition. Damage, then as now, can result from inadequate snow cover and inappropriate equipment. Recent seismic data, both 2-D and 3-D, have been acquired in a much more environmentally sensitive manner.

Offshore seismic data are acquired using patterns and spacing similar to those used in onshore acquisition. These data can be acquired only when the sea is relatively ice-free and boats can maintain long uninterrupted traverses. A high noise level is associated with marine acquisition, and it negatively affects marine organisms, especially whales.

4-D visualization adds the element of time to 3-D seismic databases. A reservoir's fluid viscosity, saturation changes, temperature, and fluid movements can be analyzed by time-lapse monitoring in three dimensions (DOE 1999). The time-lapse picture is built out of data re-recorded, compared, and plotted by computer onto the 3-D model. Additional data, such as well logs, production information, and reservoir pressures, may be integrated into the time-lapse imagery. The resulting information provides geologists and others with data that are valuable for both exploration for and management of existing resources. The exploration element comes from the greater ability to predict the best locations for exploratory drilling.

The 3-D seismic-data acquisition and 4-D visualization technologies provide a number of environmental benefits (DOE 1999). They include more accurate exploration well-siting that reduces the number of dry holes and the number and length of ice roads and the number of ice pads that have to be built; generation of less drilling waste and decreased volumes of materials that are thereby lessening the possibility of a spill or other accident; better understanding of flow mechanics so that less water is produced relative to oil or gas; and increased ability to tailor operations to protect sensitive environments. Overall fewer wells are required in order to evaluate and produce the reserves.

Nonetheless, considerable concern has existed regarding the effects of any seismic activity conducted either on land during winter or at sea during the open water season (Van Tuyn 2000). Land-based seismic-data acquisition with its large vehicles and numerous traverses across the tundra has left scars of the vehicle paths, some of which have been slow to heal and recover. At sea, migrating bowhead whales have been deflected by noises generated by seismic exploration and drilling.

The 3-D seismic-data acquisition programs require more closely spaced grids, a few hundred feet between lines as opposed to several kilometers with standard 2-D seismic programs. This closer spacing has the potential to affect a greater amount of the tundra surface. These trails are often highly visible the following summer, in part because the old dead vegetation has been flattened by the vehicles and the green new vegetation can be more readily seen in sharp contrast to the undisturbed surrounding areas.

The closer spacing of the seismic traverses may also increase the risk that denning polar bears may be disturbed. This risk could be lessened by studies of bear denning sites and planning the acquisition programs accordingly.

Remote Sensing

Remote-sensing techniques such as infrared photography have been used to design and locate roads and facilities, such as development facilities and ice roads and ice pads, to reduce effects on the environment. Satellite infrared photography has been utilized to facilitate habitat mapping in the Alpine field (Lance 2000). The environmental benefits come from the avoidance of critical habitat and better design of facilities that must be placed within less than ideal locations. No negative consequences have been identified with the use of this technology.

Ice Roads/Ice Pads

Arctic tundra is easily disturbed and slow to recover from damage. Disruption of tundra may also have a pronounced effect on permafrost and result in thawing and erosion. Historically, roads to exploration well sites were built of peat, bladed bedrock, or gravel, causing long term damage to tundra that remains evident after forty or more years. Drilling pads were similarly built of gravel or bulldozed bedrock in some areas of the National Petroleum Reserve-Alaska during the Navy exploration efforts in the 1940s and 1950s. Because of these factors and potential damage from transporting equipment across the tundra either in the summer or winter, ice roads have replaced gravel roads and have become the means of access to isolated drilling locations. In a similar fashion, ice pads have become the standard for exploration drilling sites, eliminating the need for gravel to build pads and cleanup after drilling. All onshore exploration drilling is done during winter and all materials necessary for drilling a well, including the drilling rig, are moved to and from well locations on ice roads.

An ice road 6 in. (15 cm) thick and with an average width of 30 to 35 feet (9 to 11 m) would require 1 million to 1.5 million gallons of water per mi (620,000 to 930,000 gallons of water per km) of length (Van Tuyn 2000). BP Exploration (Alaska), Inc. reports that the ice roads are generally 12 to 18 in. (30 to 46 cm) thick. Frequently, exploration activity within a specific area requires more than one drilling season; therefore, more than one ice road may be built from the staging area(s) to the same drilling site or prospect. To avoid possible damage from multiyear usage of the same area, any subsequent ice road is offset by at least a road width from previous ones.

A 6-acre (2.4 ha) drilling pad, 12 in. (30 cm) thick would require approximately 500,000 gallons of water (Van Tuyn 2000). The ice pads provide a solid, stable base from which to drill an exploration well. Upon completion and abandonment or testing of the well, the rig and all support facilities are moved off location and the pad is allowed to melt. The result is a very low impact operation, and usually the only indication of the drilling activity is the abandoned wellhead.

In special situations, specifically where drilling and evaluation are expected to require either an extended drilling season or two drilling seasons, insulated ice pads have been utilized. BP Exploration used such a system when drilling the Yukon Gold No. 1 and Sourdough No. 2 wells in the 1993-1994 drilling season (DOE 1999). A 190 by 280 ft (120 by 85 m) ice pad was built in March 1993 and covered with wind-resistant insulating pads. The pads remained in place over the summer and were removed in October. Drilling began in mid-November, two months ahead of conventional Arctic practice. With this advanced drilling start, the Yukon Gold well was completed, the rig moved to the Sourdough site, and that well completed the same season. This would not have been possible with a conventional ice pad.

There is the potential for some level of short-term damage in areas that have either experienced low snow fall or removal of snow by high winds, thus creating substandard show cover conditions. However, in most instances there is little evidence of either the ice road or ice pad once the snow cover is gone.

The use of the ice-road and ice-pad technology reduces the need for gravel during the exploration phase of oil and gas activity. Smaller volumes of gravel are mined during the history of a given field, less area is covered by gravel, and there is little recognizable damage to the tundra. The use of an insulated pad allows the drilling of more wells in a single season, reducing the need to build ice roads in two seasons to serve the same general area.

The older technologies had greater potential to seriously disrupt tundra, thaw permafrost, and mar the viewscape. These effects can persist for many years and many damaged sites have not been adequately remediated. Although the use of ice roads and pads has largely eliminated those problems, a different set of potential effects has been identified. Insulated ice pads have some degree of influence on the underlying tundra, simply because the area loses a growing season, but these effects have not been studied.

The construction of ice roads and pads relies on a ready and plentiful supply of water. Water is drawn from rivers or lakes, existing ice is crushed or chipped and spread along the prescribed roadway or pad site. Concern has been expressed that the extraction of such large volumes of water may endanger fish and drinking water resources. Areas such as the Arctic National Wildlife Refuge have low lake densities and a reliable source for water to build ice roads/pads may not be present. At this time, there are few reliable data that address the controversy over the appropriate use levels for water in the construction of ice pads/roads.

Rolligons and the Arctic Drilling Platform

Potential problems associated with exploration drilling in areas with limited freshwater supply or shortened ice road seasons may be alleviated by the use of low ground-pressure vehicles (Rolligons) and the Arctic Drilling Platform. Rolligons can extend the drilling and off-road seasons on the North Slope. Current Rolligons put 4 to 5 psi of footprint pressure on the tundra, but that would be reduced to 1 psi per tire, depending on the load and the tire size (Rolligon Corporation web site, www.rolligon.com; Petroleum News Alaska 2002). The vehicles have been used to move drilling rigs to remote locations on the North Slope. Their primary use would probably be to access locations that are far from current infrastructure and where the economics of the operation favors their use over the costs and the associated delays of building an ice road.

The Arctic Drilling Platform is an adaptation to land of offshore technology. The platform is light and mobile. It can eliminate or reduce the need for ice roads or ice pads (Petroleum News Alaska 2002; Anadarko, unpublished material, 2002). The platform is self contained and elevated. It can serve as a temporary drilling facility or a long-term production facility. It is supported by steel pilings that contain coils for circulating hot or cold fluids. The elevated platform consists of interlocking aluminum components (12.5 ft by 50 ft [3.8 m by 15 m]) with reinforcing elements and rests on a base of shallow containers that capture any deck fluids or other spillage. The components are transported by Rolligons, thus eliminating the need for ice roads, as well as ice pads.

A small version of this system is being used by Anadarko during the 2002-2003 drilling season, on a 3,000 to 3,500 ft (914 to 1067 m) gas hydrate core well south of the Kuparuk oil field.

DRILLING AND COMPLETION TECHNOLOGIES

An oil reservoir is part of a porous and permeable layer of rock in which the oil is trapped. On the North Slope, each production well is designed to produce from a subsurface area of at least 80 acres (32 ha). Wells are located on gravel pads and are drilled vertically through approximately 2,000 ft (600 m) of permafrost. Once through the permafrost, the bit is directed toward the desired bottom hole location. The number of wells per pad generally ranges from 16 to 40 (BP Exploration Alaska, Inc. and ARCO Alaska, Inc. 1997). The size of the pad and associated facilities is largely governed by the spacing between wells, and the number of pads is a function of the size of the area that can be drained by the wells on a pad. Historically, production wells were either straight or deviated holes and the number per pad was limited; hence, the number of pads needed to drain a specific area was high. The lateral reach of deviated holes rarely exceeded the true vertical depth (TVD) of the well. New technologies have done much to improve the lateral reach of a well and to reduce the size and number of well pads.

The technologies developed over the last two decades have greatly reduced the size of the "footprint" left by the industry when developing an oil field. Wells may be much more closely spaced, far larger areas developed from a single small pad, the mud systems are less toxic, and reserve pits have been eliminated.

Coiled Tubing

The use of coiled tubing is particularly valuable in sensitive environments such as the North Slope. Coiled tubing technology is quieter and has far less impact on a drilling site than conventional equipment (DOE 1999). The technology dates from the 1950s, but only after rapid technological advances in the late 1980s did it come into common use. The tubing is mounted on a large reel and is a continuous flexible coil that is fed into the hole. The use of coiled tubing does not require the repeated "tripping" out of the hole to add additional pipe segments. One of the byproducts of coiled tubing drilling is a significant reduction in the volumes of drilling fluids compared with conventional drilling. Coiled tubing mud volumes are commonly less than half those required or generated by conventional drilling practices (DOE 1999). In many wells, conventional methods are used to drill the initial hole and then coiled tubing is utilized to drill horizontal segments or multilateral completions. The coiled tubing technology is also commonly used for slim-hole drilling (i.e., a rotary borehole of 5 in. [12.7 cm] or less, or a drill hole of the smallest practical size) and reentry projects.

The use of coiled tubing technology has substantial environmental advantages over the conventional drilling technology, but does have some limitations in its application. The primary benefits include (DOE 1999): reduced mud volumes and drilling waste; cleaner operations, no connections to leak mud; reduced operations noise; minimized equipment footprints and easier site restoration; reduced fuel consumption and emissions; reduced risk of soil contamination due to increased well control; and better well-bore control.

These advantages clearly support the use of coiled tubing whenever it is technically feasible. Many of the newer fields such as Alpine use this technology almost exclusively in conjunction with extended-reach horizontal drilling. No detrimental environmental effects are known to be associated with the introduction of coiled tubing technology to the North Slope.

Horizontal Drilling

Horizontal drilling became a reality in the 1970s due to advances in computers, steerable down-hole motor assemblies, and measurement-while-drilling tools. A horizontal well is drilled from an initially vertical well-bore at an angle between 70° and 110°. Vertical or near vertical wells drain oil from a single hole and have limited contact with the oil-bearing interval (usually limited to the vertical thickness of the rock unit). Horizontal wells penetrate the formation up to 8 km (5 mi) or more from the vertical well bore allowing more oil to drain into the well.

The results are a greater number of wells per pad, closer well spacing on the pad, and fewer well pads than using the old technology. Well spacing has decreased from 120 ft (37 m) or more to as little as 10 to 15 ft (3 to 5 m) between wells (BP Exploration Alaska, Inc. and ARCO Alaska, Inc. 1997). Pad size and radius of reach of the wells on the pad have undergone remarkable changes since the start-up of the Prudhoe Bay field in the 1970s. An example of the reduction in pad size and corresponding area of reach is summarized below (Revkin 2001):

- 1970—Prudhoe Bay Drillsite 1; covers 65 acres (26 ha), has an effective reach radius of 1 mi (1.6 km), and produces from an area of 2,010 acres (814 ha).
- 1980—Kuparuk Drillsite 2B; covers 24 acres (10 ha), has an effective reach radius of 1.5 mi (2.4 km), and produces from an area of 4,522 acres (1,831 ha).
- 1985—Kuparuk Drillsite 3H; covers 11 acres (4 ha), has an effective reach radius of 2.5 mi (4 km) and produces from an area of 12,500 acres (5,100 ha).
- 1999—Alpine Pad #2; covers 13 acres (5 ha), has an effective reach radius of 4 mi (6 km), and produces from an area of 32,154 acres (13,022 ha).

The marked increase in drillable area per pad, as demonstrated at Alpine, is largely due to the extensive use of horizontal drilling technology, although Pad #2 is connected to the rest of the 97-acre (39-ha) Alpine site.

The environmental benefits include smaller footprints requiring less gravel and fewer wells to produce the same volume of hydrocarbons. These more effective drilling programs require less water and subsequently generate less drilling waste. Horizontal drilling results in smaller and fewer pads than did the older technologies, but gravel is still needed and effects on tundra and permafrost may result from gravel mining and emplacement. The closer spacing of well-bores has the potential to increase the rate at which permafrost thaw bulbs form, reducing surface stability and causing subsidence. However, some factors can limit the application of this technology (MMS 2001a, Vol IV, Appendix D).

Multilateral Drilling

Multilateral drilling, a variant of the horizontal drilling technology, creates an interconnecting network of separate, pressure-isolated and reentry accessible horizontal or high-angle boreholes surrounding a single major borehole (DOE 1999). Multilateral drilling is most effective in reservoirs that have isolated accumulations in multiple zones, have oil above the highest perforations, have lens shaped pay zones, are strongly directional, contain distinct sets of natural fractures, and are vertically segregated with low transmissibility.

The environmental benefits are similar to those achieved with horizontal drilling and include fewer drilling sites and smaller footprints, less drilling fluids and cuttings, and protection of sensitive habitats and wildlife. Multilateral drilling poses no recognized risk to the environment other than those associated with horizontal drilling.

Measurement-While-Drilling (MWD)

Conventional down-hole logging practices consist of running a variety of remote sensing tools down a borehole prior to setting the surface casing, before any intermediate casing strings, and prior to completing the well at total depth. These tools are on wire-lines and are lowered into the uncased hole and pulled back to the surface. The tools record specific types of data as they are withdrawn from the hole. These data are then used to evaluate the rock type, reservoir properties, hole integrity, and the other features concerning the physical environment of the well-bore. The procedure is routine, but it can be a risky because irregularities in the hole can result in stuck or even lost tools. Conventional logging can be especially risky in a highly deviated or horizontal hole where there is an increased probability that the tool, while being pulled out of the hole, may become snagged on a resistant rock projection or become buried by loose debris collapsing into the hole.

Additionally, these important data are not available to the geologist until some time after the well or interval has been drilled. This delay may vary from hours to days or even weeks. An example would be the desire to correlate the drilled section with that seen in a well some distance away, in order to predict a coring point or anticipate a stray high-pressure sandstone.

Measurement-while-drilling (MWD) technology can provide data virtually as the intervals are drilled. Additionally, sensors provide directional information and other key data that facilitate more effective geosteering and trajectory control (DOE 1999). The recording sensors and other necessary equipment are housed in the drilling assembly at the bottom of the pipe-string, just a few meters above the drill bit.

Conventional logging tools are still run in many wells and provide a wide range of critical data that are not currently replicated by the MWD tools. Thus, the current technology is a blend of the older wire-line tools and the real-time MWD instruments. Geologists and drilling engineers can benefit from the best of both worlds in today's drilling environment.

Because of its real time capability, the MWD technology can be used to avoid formation damage by alerting the rig crew of problems before they become too serious to correct; similarly there is a reduced possibility of blowouts and improved overall rig safety. This technology is also a contributing factor in the reduction of drilling waste volumes because it facilitates horizontal and multilateral drilling practices and provides better well-bore directional control.

However, the conventional logging package requires long trips to remove pipe from the hole and run a number of wire-line tools down the hole to record data. This process can take several hours to as much as a few days, depending on the number of tools to be run and the depth and condition of the hole to be logged. Repeated flushing of the hole can cause formation or hole damage and result in sloughing of materials into the hole from the walls of the well. The potential for loss of a tool assembly exists. If a tool cannot be extracted or milled up, the hole must be sidetracked and re-drilled, thus creating more waste and extending the duration of the drilling process. The MWD technology significantly reduces this risk and its associated impacts.

Light Automated Drilling System (LADS)

The construction of ice roads and ice pads in remote areas requires an abundant water supply. There is legitimate concern regarding means of access in areas that lack sufficient water and/or fresh-water ice to build roads or if global warming were to prevent the use of ice roads.

A possible solution to this problem, the Light Automated Drilling System (LADS), is in the research phase and is being considered for use on the North Slope. This potential drilling system is expected to be a light-weight drilling rig that can be easily broken down into several components and transported across tundra in winter by light impact vehicles that would not require ice roads. This system or others like it could be adapted to work in areas that lack sufficient water for ice roads or during mild winters when it would not be possible to build an ice road, transport a rig to a drilling location(s), and return it to the staging area.

The principle benefit of LADS would be to reduce the need for water to build ice roads. The primary drawback from the environmental perspective would be the increased risk of damage to the tundra while transporting rigs between locations in the absence of adequate snow cover. The same concerns exist as are presently expressed for seismic activity but on a much reduced scale.

PRODUCTION TECHNOLOGIES

Production and associated operations are the longest-term activities in an oil field. The life of major oil fields on the North Slope is expected to be on the order of 30 to 40 years, occasionally as much as 50 years. During this time pipelines, production facilities, waste disposal systems, water treatment plants, injection facilities, road systems, and other specialized units continue to operate.

Industry attempts to produce the maximum amount of oil (gas) at the least cost in order to remain competitive and viable in the event of competition for funding or a low oil/gas price environment. The most cost efficient technologies are the obvious choice of the operators. It is not surprising that in the early phases of development and production some of these choices have proven to be less than optimal from an environmental perspective. The use of reserve pits for the disposal of used drilling muds, cuttings, and other waste is one such example.

Today, on the North Slope, as fields continue to be discovered, developed and produced, there continues to be the need for new pipelines, production facilities, waste disposal wells, etc. To reduce the environmental effects of these activities, new technologies have been developed or adapted for use on the North Slope. New methods do not eliminate the need for gravel, water, and other materials, but they reduce their use and cause less disturbance, therefore reducing the potential negative effects associated with wastes and road and pipeline construction.

Enhanced Oil Recovery (EOR)

This technology, discussed in Chapter 4, involves the injection of formation/source water, natural gas, and miscible fluids into the producing reservoir to maximize recovery of hydrocarbons. In this process, not only is more oil recovered per well, but much of the waste water associated with oil production is reintroduced into the reservoirs from which it was produced. Many problems that formerly were handled by surface or reserve pit disposal techniques are solved.

The principal environmental benefits are greater recovery of oil without a proportionately greater number of wells and their associated waste, environmentally friendly disposal of produced water, and reduction of emissions that would be associated with the flaring of excess produced gas. Few negative environmental effects are associated with EOR. The primary unease is in regard to spills of produced water and the remote possibility that a reservoir may be over-pressured through the injection process, cause fracturing to the surface, and allow oil and other fluids to escape to the pad and/or tundra.

Waste Disposal

From the 1940s to the 1980s, most well-associated wastes were either stored in reserve pits or handled through other surface disposal means such as incineration. The reserve pits were prone to seepage and spills, and they contained undesirable metals and volatile organic compounds. These did, and still do present environmental risk, especially at old, unclosed remote exploration sites.

The reserve pit closure program was instituted in 1996. To date, fifty percent of approximately 600 reserve pit sites have been closed. The ADEC required submittal of closure plans for all sites by January 28, 2002 (Maham 2001). These plans, which do not require full restoration of the sites, have been submitted (ADEC 2002). Down-hole disposal of wastes by injection into subsurface disposal intervals is utilized in all present-day exploration wells and producing fields.

This mode of waste disposal is an effective and non-contaminating method of removing many unwanted materials from the surface environment. The grind-and-inject project was undertaken to dispose of drilling muds and cuttings stored in reserve pits. Other wastes processed through the grind-and-inject plant include: Class II, RCRA-exempt oily wastes, and drilling muds and cuttings from ongoing drilling operations. As of May 31, 2000, injection at the Surfcote pad included 5.2 million bbl (218.4 million gallons) of water, 16.4 million bbl (688.8 million gallons) of slurry containing 1.1 million tons (1 million metric tons) of excavated reserve pit material and drilling solids, and 166 million bbl (7 billion gallons) of fluid from ongoing drilling operations (Bill 2000).

Annular injection is an environmentally safe method of disposing of drilling muds and cuttings, and the injection of Class I and Class II materials into discrete disposal zones has provided a mechanism for the handling of produced formation waters and other associated wastes (API 1996).

However, a large number of unclosed reserve pits remain at remote exploration well-sites. No adequate plan is in effect to handle the possible pollution and resultant damage from poorly sealed and covered pits. The annular injection process has some potential to create or take advantage of poor casing or cement jobs and result in leakage to the surface. This has occurred on several occasions, but with no contamination of permafrost. Worries regarding subsidence and marine contamination have been expressed, but the existing evidence indicates that subsidence is not a concern and disposal units are effectively and naturally isolated from any contact with the ocean or seafloor.

Roadless Construction

Prudhoe Bay, Kuparuk, Endicott, and other early generation oil fields were developed, facilities and pipelines constructed, and distinct operating areas joined together through a network of gravel roads. This required large volumes of gravel that have been extracted from 13 gravel mines. The U.S. Fish and Wildlife Service has estimated that more than 60 million yd^3 (46 million m^3) of gravel have been mined to supply the constructions needs of the North Slope oil fields (Van Tuyn 2000). Data from the Department of Natural Resources (DNR) place the volume of gravel extracted from 1974 to date at 57,880,481 yd^3 (44,252,803 m^3).

Because of a decrease in scale of facilities and well pads the rate of demand for gravel is decreasing. Also, new roadless construction methods for remote operations have eliminated much of the need for gravel in road construction. As an example, the Alpine construction was done during the winter with equipment, personnel, and modules transported to the site via ice road. Similarly, the pipeline from Alpine back to the existing pipeline infrastructure at Kuparuk was built using ice roads. Gravel was used to build two production pads, a 3 mi (5 km) road between the two Alpine pads, and an airstrip, totaling about 97 total acres (39 ha).

Future oil field development will be based on refined variants of the Alpine model. Pads will be small and few in number and construction will be largely a winter activity with transportation via ice roads. The use of gravel will be appreciably reduced. However, the scarcity of water in some areas, climate change, and other factors could make use of gravel roads more attractive economically and practically in some areas.

The issue of removing and possibly cleaning the existing volumes of gravel, some of it contaminated from spills related to a variety of causes and fluids, is not resolved. In some instances, the operators have removed gravel, cleaned it if necessary, and reused it elsewhere, but the truly massive task of removal or remediation awaits the abandonment of the fields.

The primary environmental benefits are use of less gravel and reduced damage to the tundra. This practice may eventually be efficient enough to be implemented through the reuse of gravel from older abandoned roads and pads.

The environmental concern is the large volume of gravel on existing roads and pads of the major North Slope oil fields. The effects this material has on caribou movements/deflections, especially at roads in close proximity to elevated pipelines; the potential for ponding waters; destruction of the tundra; and long term effects on permafrost may be real and significant. There appears to be a genuine potential for large-scale gravel mining and usage to result in environmental effects that accumulate on the physical and biological components of the region.

Pipeline Construction

Among the standard practices utilized in the construction of pipelines are gravel maintenance/construction roads, elevated river crossings, and block valves to reduce the likelihood and sizes of leaks and spills. Recent developments have lessened the environmental effects of pipeline construction, the hazards to the pipeline due to flooding, the probability and severity of leaks, and impediments to caribou movement. These new approaches were all used in the design and construction of the Alpine oil pipeline (Lance 2000), which was built largely during the winter and construction using ice roads. The lack of a gravel maintenance road removes one potential barrier to caribou movement, reduces the volumes of gravel required for the Alpine-like projects, and the amount of tundra impacted by burial.

The Colville River pipeline crossing posed a considerable challenge. During breakup and the associated flooding, the river is almost a km wide and it could destroy an above ground pipeline or erode deeply enough to expose and rupture a line buried in a surface trench. ARCO Alaska, Inc., elected to use horizontal directional drilling (HDD) to position the pipeline deep beneath the river channel (Lance 2000). More than 4,000 ft (1,200 m) of pipeline were placed 100 ft (30 m) below the river. There was no need to erect pylons for an overhead crossing or trench within the floodplain of the Colville during the winter. However, 8.3 million liters (2.3 million gal) of drilling muds were lost under the Colville River in 1998; its fate is not known.

After conducting an oil-spill isolation strategy study that reviewed ways of meeting federal leak-containment regulations, ARCO Alaska, Inc. elected to use 12 to 14 m (39 to 46 ft) high vertical loops on the Alpine pipeline in lieu of the more conventional block valves. The study concluded that when used in tandem with emergency pressure-letdown valves or divert valves, vertical loops would contain drain-down-related spills as well as block valves, while offering operations and maintenance efficiencies (Pavlas et al. 2000).

The loops are better than manual block valves for reducing catastrophic failures and they provide protection levels similar to those achieved by remotely-actuated valves for leaks of all sizes. They are not themselves potential leak sites, as valves are, but they do not provide any substantial benefit over block valves for pinhole leaks. With approval from the Department of Transportation, the loops were placed at river crossings and high points along the line.

These new pipeline construction methods greatly reduce the environmental effects on tundra, provide for a safer line and lessen the probability of spillage due to river induced pipeline damage. They also more effectively limit the size of catastrophic spills. However, the placement of a pipeline at depth beneath a river could make detection and cleanup of a spill in the buried segment difficult. The preexisting and predominant North Slope pipeline technology presents impediments to caribou movement when in close proximity to roads, and river crossings are sites of potential severe environmental consequences if a spill occurs. The accumulation of effects of continued construction of pipelines and road systems could increase the magnitude of displacement of the calving caribou away from the coastal strip and prime forage/insect relief areas.

Remote Sensing

Satellite infrared photography was used in the Alpine planning and construction phases for selecting the locations of pads and other structures to avoid sensitive, critical habitat. Remote sensing devices have the potential to serve other needs on the North Slope. One of the more recent applications may prove to benefit several diverse areas. A Forward Looking Infrared sensor system (FLIR) can be used to detect pipeline leaks. An airborne FLIR unit is an effective tool in surveying pipelines for potential corrosion and detecting leaks. The system may also have use as a spill response tool for tracking spill movement under ice and snow. FLIR can image a spill site and supply pertinent information either as video footage or as a video frame registered map.

An additional FLIR application is locating large mammals. Although its effectiveness is yet to be fully determined, this system might facilitate the location of polar bears dens. Such an application could be used to plan seismic surveys in such a way as to avoid denning bears.

The potential environmental benefits include avoidance of critical habitat, leak and spill detection, corrosion detection, and planning of seismic and other winter programs to avoid denning bears. There are no obvious environmental drawbacks to these technologies.

Appendix E:

Aeromap Analyses and Data

The information summarized in Chapter 4 on the history of industrial development includes novel analyses created expressly for this report by Aeromap Inc. (Ambrosius 2002). Most of the raw data were supplied by BP, Inc. The methods and details of that assemblage are given here.

AEROMAP U.S.

INTERNATIONAL PHOTOGRAMMETRIC CONSULTANTS

The National Academies
National Academy of Sciences

January 30, 2002

Memorandum:

Calculation of Area Impacted by Oil Field Development North Slope Alaska

Rev.1 02/07/02

This memorandum is a description of the calculations of the area of impact due to oil field development on the Alaskan North Slope.

The impact area was calculated through the use of Industry owned large-scale topographic base maps and historical aerial photography. Area calculations were done for the years 1968, 1973, 1977, 1983, 1988, 1994 and 2001. The geographic area of this project is limited to: north of 70° 5' north latitude, and between 145° 55' and 151° 20' west longitude. A more detailed area description is included on page 7.

For the purpose of these calculations "impact" was defined as the footprint of a gravel facility, the area used for gravel extraction, any overburden piles, or any visible marks or scars on the tundra that persisted for a period of 10 years or more.

All facilities related to the oil field development were included for the purpose of these impact area calculations. No distinction was made between industry owned facilities, contractor facilities, or State of Alaska facilities such as Deadhorse. Those portions of the Trans Alaska Pipeline System and the DOT's Dalton Highway that fall within the study limits are included. Only the Distant Early Warning (DEW Line) military sites and any native owned or other private property sites are excluded.

These area calculations do not include the exploration work done by the U.S. Government in NPRA, exploration wells or seismic camps in the foothills of the Brooks Range, the DOT Dalton highway that falls outside the study area limit, nor any of the Trans Alaska Pipeline system that fall outside of the study area limit. The geographic area of the project was limited to the area for which detailed maps and photos were available for my use.

The area calculations were divided into four geographic regions for each year:

1) West of Kalubik Creek
2) Kuparuk River to Kalubik Creek
3) Foggy Island to Kuparuk
4) East of Foggy Island

Oil field facilities and roads are raised gravel structures that have well defined edges. Deep pit gravel mines (more than 20 feet deep) also have well defined edges. These items are mapped to 1"=500' standards through photogrammetric methods.

Exploration activity before 1978 sometimes took place without raised gravel pads or roads. Prior to 1978 some gravel was extracted from riverbeds by simple grading material into a pile and then hauling it off. Some of these items are well defined in current aerial photos while others are not. The area limits for those items that are not well defined were interpreted from historical photography.

The procedure used for the area calculations involved the following steps:

- A 'footprint' polygon was extracted from the most recent topo map CAD files available from the oil industry. This polygon was placed in a single CAD file and was used as a 'base' for construction of all years studied. The file contained only the areas currently covered by gravel facilities, roads, and mine excavations. Exploration facilities, riverbed gravel extraction, and other impacted areas (disturbed tundra not covered by gravel facilities) were not included.

- The 1968 aerial photos were examined to determine the impact area for that year. The 'base' reference file was used to help locate and define the areas as they appeared in 1968. Well-defined gravel facilities that were a match to what was observed in the 1968 photos were copied from the 'base' reference file into the 1968 CAD file. From an examination of the 1968 photos other impacted areas were then also digitized into the 1968 file with the aid of the current industry topo maps as a backdrop.

- The 1968 CAD file was then copied and renamed 1973. The 1973 photos were examined, those polygons from the 'base' reference file that matched were copied into the 1973 CAD file, and other impacted areas were digitized as above.

- The procedure was repeated for the years 1977, 1983, 1988, 1994, and 2001. A CAD file that contained all impact areas up to that time was created for each year. Each year depicts a cumulative impact up to that time with no consideration for "rehabilitation". These CAD files are the source for the calculations in the accompanying excel tables. Calculations were done using ARC View software in an Alaska State Plane, zone 4, NAD27 projection.

- An additional column was created in the excel tables labeled '2001 current'. Areas that appear to have been rehabilitated through either natural process or through industry efforts have been subtracted from the impact area. This is my best effort at an objective interpretation of the "current conditions"; it does NOT represent the 'Industry viewpoint'.

CALCULATIONS

Exploration Sites

Access to exploration wells from 1963 through 1973 was achieved by three methods each had a varying degree of impact on the tundra. The original table from the project proposal included only Peat Roads; it was expanded it to include all three.

These methods of access were only used prior to 1973. Later permanent production facilities and gravel roads were constructed over some of these early access routes when possible.

a. **Tractor Trails / Tundra Scars** – For some early exploration wells the rig was simple parked on the frozen tundra and shimmed up on timbers to level. Access was from driving over the frozen tundra. By continued use of these routes after spring thaw ruts and tundra scars were produced that have persisted for many years. All of these rutted or scared areas are included in the cumulative impact area calculations.

   Natural processes have since revegetated areas where the routes crossed well-drained high ground. Other low lying wet areas remain marked by well-defined water filled depressions or ditches. In the '2001 current' column of the table those areas that appear to be rehabilitated have been left out.

b. **Peat Roads** – For a few years exploration well access and rig movement was done over peat roads. Peat roads were constructed by using a bulldozer to blade the native soil into a mound, one bulldozer on each side of a route centerline. The result was a pair of parallel shallow ditches on either side of a mound. The mound was graded and packed and when frozen provided a roadbed. Peat roads have left a very well defined mark on the landscape still visible today. The peat roads have become revegetated through natural processes and most have shallow ponds on each side. However, the construction of peat roads has altered the native vegetation patterns and the drainage patterns, it has created a new habitat type that is different than was originally present. Attempts to return these areas to the original state would likely create more impact.

In the '2001 current' column of the table the area covered by peat roads has been retained because they have produced a tangible impact on the native environment that remains today.

c. **Exploration Access Roads of Thin Gravel & Frozen Tundra** – A third method of access was a combination of; a) the placement of a thin layer of gravel over uneven ground and, b) driving over frozen tundra where the ground was already smooth and even. In the areas where no gravel was placed a visible scar on the tundra was observed that persisted for as many as ten to fifteen years, probably a die off of vegetation through repeated passage. All of these areas of thin gravel or vegetation die off are included in the cumulative impact area calculations.

Some of the tundra scars have disappeared by year 1994 or 2001 revegetated through natural processes. Some of the low-lying wet areas where a thin layer of gravel was placed also appear to have become revegetated through natural processes. These may be considered rehabilitated. Other well-drained areas where gravel was placed have remained pretty much as they were when first constructed. In the '2001 current' column of the table those areas that are consider rehabilitated were left out.

d. **Exploration Site - Disturbed Area in Addition to Gravel Covered Area –**

i) Early exploration wells were drilled in winter when the tundra was frozen. For some wells the rig sat on the tundra and was leveled with timbers, no gravel was used at all. Activity around the rig caused some vegetation die off, other areas were rutted and scared by vehicle activity, sometimes pits were dug in the tundra. After the rig was demobilized from the site some pits were filled in, material that was dug up was spread around, some sites appears to have been graded. All of these disturbed areas are included in the impact area calculations.

Over time some of these disturbed areas have become revegetated through natural processes. In the '2001 current' column of the table those areas that are revegetated and considered rehabilitated were left out.

ii) For some exploration wells a thin layer of gravel was used to level the site. Again, activity around the rig caused vegetation die off, other areas were rutted by vehicle activity, and pits may have been dug in the tundra. After the rig was demobilized the thin gravel may have been left in place or it may have been spread around or used to fill in pits. The material that was dug from the pits may have been spread around, some sites appear to have been graded. All of these disturbed areas are included in the impact area calculations.

Over time some of these disturbed areas have become revegetated through natural processes. In the '2001 current' column of the table those areas that are revegetated and considered rehabilitated were left out.

iii) For some exploration wells a gravel pad was constructed, normally 3 to 5 feet thick with a pad and camp area and reserve pits constructed at grade by use of gravel dikes or berms. These sites generally had little to no activity off of the pad that impacted the tundra, however for the few that did these areas are also included in the impact area calculations. Some of these gravel exploration pads have been revisited by industry and 'closed out' to State of Alaska specifications in recent years. The close out procedure may have included regrading some of the gravel found onsite to cover the reserve pits or it may have included breaching the dikes to prevent ponding of water. Sometimes these activities have slightly increased the disturbed area. Some areas have been revegetated through natural processes over time. All of the disturbed areas are included in the impact area calculations.

In the '2001 current' column of the table those areas that are revegetated and considered rehabilitated were left out.

e. **Exploration Site - Tundra Covered by Gravel** – These are the footprint area of those exploration sites that are raised gravel pads. The area calculation is cumulative and includes some sites that are no longer visible on the aerial photography. Some of the sites were located on barrier islands and have since washed away a few others have become thermocarsted and revegetated by natural processes.

In the '2001 current' column of the table any sites that were washed away or that have been revegetated were left out.

f. **Exploration Airstrips Thin Gravel / Tundra Scar** – Some of the early exploration wells were accompanied by airstrips that were a combination of the placement of a thin layer of gravel over uneven ground and a thin ice pad where the native ground was smooth and even. In the areas where no gravel was placed a visible scar on the tundra was observed that persisted for as many as ten to fifteen years, probably a die off of vegetation through repeated passage. All of these areas of thin gravel or vegetation die off are included in the cumulative impact area calculations.

Areas where gravel was placed have remained pretty much as they were when first constructed. The tundra scars have disappeared by year 1994 or 2001, revegetated through natural processes and are considered rehabilitated. In the '2001 current' column of the table those areas that are consider rehabilitated were left out.

g. **Exploration Islands** - The exploration island area calculations are only for that portion of the island that is above sea level in the same manner as was done for "Causeways". For the cumulative figures every island was included, even after an island may have been washed away or removed.

In the '2001 current' column the area of all islands that are no longer in place were left out and those that were changed by erosion were modified to show current conditions.

Production Facilities

h. **Roads** – Gravel roads for general transportation are normally five feet thick and vary in width. Some gravel roads were constructed for pipeline inspection or maintenance and are not intended for general use, these may be less than five feet thick. All of these roads are included in these calculations. Areas were calculated from the toe of the roads.

i. **Causeways** – The causeways are generally constructed to be about twelve feet above Mean Sea Level; side slopes are approximately 7 to 1. The depth or elevation of the seabed beneath any of the causeways varies. The area included in these calculations is only for that portion of the causeway that is above Mean Sea Level, no effort was made to interpolate the area of seabed actually covered. The area of the causeways was reduced from 1994 to 2001 due to the construction of a breach at West Dock and another at Endicott.

j. **Airstrips** – Area calculations include both active usable airstrips and airstrips that were constructed for exploration activities that are no longer in use. All of these airstrips were constructed from gravel and are generally a minimum of five feet thick. Though some of the exploration airstrips have severe thermocarsting and are no longer useable the area of impact numbers remain under this 'airstrip' heading. The gravel from some airstrips has been removed for use in construction of other facilities. In both the '2001 cumulative' and the '2001 current' columns of the tables those area that have been removed and reused were left out. The calculations for those removed areas are recorded under the "Gravel Removed From Tundra" heading.

k. **Production Islands** – Production islands area calculations are only for those portions that are above sea level in the same manner as was done for "Causeways". One production island is incorporated into a causeway; that area was segregated out and reported as a production island.

l. **Production Pads / Drill Sites** – Some production drilling pads were constructed over exploration sites. In these cases the area calculations are reported as 'drill sites' rather than under 'exploration sites'. At the time of construction some facilities were built in such a way as to enclose areas of tundra that are not part of the facility. Other areas that were to be used as flare or reserve pits are completely enclosed, though some were never used and appear to be native tundra with no impact. The drill site areas as calculated here include all of those parts of a facility that were intended for use as a pit as well as the areas of tundra actually covered by gravel. The tundra areas that are not part of the facility but are surrounded by the facility are not included in the area calculations.

m. **Processing Facilities** – Processing facilities are generally large pads with large equipment. In recent years a few very small pads were built in conjunction with the Badami and Northstar pipelines. These small pads are at shore fall and at either bank of rivers, they contain automated valves and a helicopter-landing pad. I included these as process facilities for area calculations, however I did not count each one as a separate facility for purposes of 'number of facilities' due to the relatively insignificant size.

   Some facilities were built in such a way as to enclose areas of tundra that are not part of the facility. Some of these areas are large and have not been visibly impacted; others are small and have filled with storm runoff or snowmelt debris. Areas intended as flare or reserve pits are completely enclosed by gravel dikes. The production facility areas as calculated here include all of those parts of a facility that were intended for use as a pit, the small impacted enclosures, and the areas of tundra covered by gravel pad. The larger tundra areas with no visible impact but surrounded by the facility are not included in the area calculations.

n. **Support Pads** – Support pads include facilities under the control of the oil industry and State of Alaška owned and leased properties that are not under industry's control. In general these facility footprints are well defined, however on occasion they have spread out unto the tundra and have then contracted back to the gravel pad. All of these areas that were used for storage or that appear to have otherwise disturbed the tundra are included in the impact area calculations.

   Over time some of these storage areas have been cleaned up, some disturbed areas have become revegetated through natural processes. In the '2001 current' column of the table those area that are considered rehabilitated were left out.

o. **Gravel Pad Removed - Site in Process of Recovery** – By year 1973 the very first gravel pad constructed, the ARCO base camp, was reconfigured. A portion of the gravel pad was removed and reused elsewhere. In every subsequent year photography examined additional areas of gravel pad or gravel road were found that had been picked up. Some areas have become revegetated through natural processes in a relatively short time. Others take as long as ten to fifteen years, while still others have remained a visible scar to this day. For the years 1973 through 1994 all gravel removed from tundra was placed in this area calculation regardless of status of recovery.

   Note that this category was used only for those areas where a raised gravel pad or road was removed; it was not used for other 'disturbed areas' or thin gravel. Also note that a few of these areas of removed gravel were in riverbeds and the 'removal' may have been caused by erosion rather then by construction equipment.

p. **Gravel Pad Removed - Site Recovered** – Those areas that are appear to be recovered by natural means or rehabilitated by industry are reported here, separately from those that remain visible scars as of 2001.

q. **Gravel Mine on Riverbed** – Gravel for facility construction was removed from the Sagavanirktok and Kuparuk Rivers (typical gravel filled meandering glacier riverbeds) by two different methods:

i) Up to 1978 gravel was removed from some portions of the riverbed by pushing portions of the gravel bars into large piles and then hauling them off with earth moving equipment. The equipment used for this surface mining left some well defined and some not so well defined tracks, pits and piles in the riverbeds. Subsequent spring flooding erased much of the evidence. I suspect that in some areas the river channels changed due to the removal of gravel and this further erased evidence of the gravel removal. From examination of the historical photography I believe that I have accurately defined the gravel removal areas. All of these disturbed areas are included in the cumulative impact area calculations.

Over time evidence of gravel removal for some of these areas has disappeared due to spring floods and the action of the river. In the '2001 current' column of the table I have subtracted out those areas that I consider to be rehabilitated.

ii) From 1973 through 2001 a side channel of the Kuparuk River has been the site of deep pit mining. This side channel floods during spring break up but is otherwise a series of oxbow lakes. From year to year dependent on the results of the spring floods these oxbows are connected by streams. A series of pits were dug from the spine road to the river delta. Some surface mining and surface grading was also done in some of these areas. All of the pits are currently full of water; those that had no surface mining at the edges appear to be natural oxbows and are indiscernible from the natural environment. Some of the pits are currently used as reservoirs and have a flat graded area for vehicle traffic next to them. All of the areas used for mining are included in the cumulative impact area calculations.

I consider the areas that were pit mined and that have no disturbed areas around the edges to be rehabilitated. In the '2001 current' column of the table I have subtracted out those areas.

r. **Gravel Mine in Tundra** – Some gravel mines were situated in tundra areas that are near rivers or streams, these have a very well defined footprint. Typically an overburden layer of mixed organics and gravel was removed and placed to the side of the mine area. The area calculations here include the footprint of the excavation as well as the overburden pile.

s. **Pipelines** – The length and number of pipelines data set was taken from the industry topo maps. On these maps individual pipelines are not shown, pipeline bundles are mapped with an annotation to denote the estimated number of pipelines in each bundle. This is the best data source available to me within the time constraints of this project schedule.

t. **Transmission Lines** – The transmission lines were extracted from the most recent industry topo maps. Theses include all known power lines that are located above ground on poles. No effort was made to research and define the many buried power lines.

u. **Number of culverts** – Culvert locations were extracted from the most recent topo where available and from spill contingency maps for areas not yet covered by topo maps (Tarn, Meltwater and Alpine). The numbers here are for culvert locations rather than for individual culverts. Many culvert locations contain more than one culvert. Large culverts (some as much as eight feet in diameter) are included here and not under 'bridges'.

v. **Number of bridges** – The bridge count includes causeway breaches as well as road bridges. These are from the most recent topo where available and from spill contingency maps for areas not yet covered by the detailed topo maps (Tarn, Meltwater and Alpine).

w. **Number of caribou crossings** – Caribou crossing numbers are from the Industry topo maps. Some caribou crossings have had pipelines built across them rather than under them in recent years. For the purposes of this count these have not been included.

The overall geographic extent of the areas included in this calculation is limited to the extent of the aerial photography and/or current topographic mapping coverage. This geographic extent includes the following townships: T10N-R04E, T11N-R04E, T12N-R04E, T13N-R04E, T10N-R05E, T11N-R05E, T12N-R05E, T13N-R05E, T14N-R05E, T09N-R06E, T10N-R06E, T11N-R06E, T12N-R06E, T13N-R06E, T14N-R06E, T08N-R07E, T09N-R07E, T10N-R07E, T11N-R07E, T12N-R07E, T13N-R07E, T14N-R07E, T10N-R08E, T11N-R08E, T12N-R08E, T13N-R08E, T14N-R08E, T10N-R09E, T11N-R09E, T12N-R09E, T13N-R09E, T14N-R09E, T10N-R10E, T11N-R10E, T12N-R10E, T13N-R10E, T14N-R10E, T10N-R11E, T11N-R11E, T12N-R11E, T13N-R11E, T14N-R11E, T10N-R12E, T11N-R12E, T12N-R12E, T13N-R12E, T14N-R12E, T10N-R13E, T11N-R13E, T12N-R13E, T13N-R13E, T14N-R13E, T10N-R14E, T11N-R14E, T12N-R14E, T13N-R14E, T14N-R14E, T09N-R15E, T10N-R15E, T11N-R15E, T12N-R15E, T09N-R16E, T10N-R16E, T11N-R16E, T12N-R16E, T09N-R17E, T10N-R17E, T11N-R17E, T12N-R17E, T09N-R18E, T10N-R18E, T09N-R19E, T10N-R19E, T09N-R20E, T10N-R20E, T09N-R21E, T10N-R21E, T09N-R20E, T10N-R20E, T09N-R21E, T10N-R21E, T09N-R22E, T10N-R22E, T08N-R23E, T09N-R23E, T10N-R23E, T08N-R24E, T09N-R24E, T10N-R24E, T09N-R25E, T10N-R25E, Umiat meridian.

<u>BASE MAPS</u>
BP Exploration (Alaska) Inc. maintains a set of topographic base maps of the North Slope, Alaska producing oil fields. These maps were produced by photogrammetric methods from 1973 through 2001 aerial photography. The map scale is 1"=500', the horizontal datum is Alaska State Plane, NAD27, based on USC&GS monuments. The vertical datum is Mean Sea Level based on a limited number of tidal observations at East Dock in 1973. The survey of photogrammetric control points was done to third order class two standards. The planned map accuracy is:

90% of the planimetric features are plotted to within 1/40 inch of their true positions.
(At 1"=500' this is ± 12.5 feet.)

Independent ground surveys have shown the horizontal accuracy to be ± 2.0 feet for gravel facilities and pipelines.

The detailed mapping covers all production facilities with the exception of the Phillips Alaska oil fields: Alpine, Meltwater, and Tarn. Less detailed 1:63,360 maps were used for the calculations in these areas.

Ken Ambrosius
AeroMap U.S.

map attachments

The result are the tables below, separated by geographic area, as interpreted in Chapter 4 and displayed in Figures 4-3 through 4-6.

Table A-Aeromap-1. Oilfield infrastructure through time for the entire North Slope.

		1968	1973 cumulative	1977 cumulative	1983 cumulative	1988 cumulative	1994 cumulative	2001 cumulative	2001 current
POINT MEASUREMENTS									
	A. Number of gravel pads								
	1. Production pads/ Drill sites	0	16	22	62	95	104	115	115
	2. Processing facility pads	0	6	10	14	18	18	20	20
	3. Support Pads (power stations, camps, staging pads, etc.)	1	36	63	98	108	113	115	115
	4. Exploration sites	3	42	63	103	104	106	103	91
	5. Exploration Islands Offshore	0	0	2	12	13	13	13	5
	6. Production Islands offshore	0	0	0	0	2	3	4	4
	7. Airstrips	1	11	15	16	16	16	16	16
	8. Exploration airstrip - thin gravel / tundra scar	0	4	4	4	4	4	4	2
	B. Number of culverts	no data	no data	no data	no data	no data	no data	1395	1395
	C. Number of bridges	no data	no data	no data	no data	no data	no data	17	17
	D. Number of caribou crossings	no data	no data	no data	no data	no data	no data	50	50
	G. Number of Landfills	no data	no data	no data	no data	no data	no data	1	1
LENGTH MEASUREMENTS									
I. Length of Roads in Miles									
	A. Road	0.0	100.0	138.8	294.2	357.7	370.0	400.1	400.1
	B. Peat Road	29.6	100.7	100.6	100.5	96.3	95.8	95.8	94.9
	C. Causeway	0.0	0.0	1.9	2.7	7.5	7.5	7.7	7.7
	D. Tractor trail / tundra scar	19.0	53.7	58.5	57.1	56.5	56.5	56.4	13.8
	E. Exp road - thin gravel / tundra scar	0.0	35.8	36.4	36.1	36.1	36.1	36.0	27.6
	TOTAL	48.6	290.2	336.2	490.6	554.1	565.9	596.0	544.1
II. Length of Pipeline Corridors in Miles									
	A. 1 pipe	no data	no data	no data	no data	no data	no data	73.2	73.2
	B. 2 pipes	no data	no data	no data	no data	no data	no data	111.9	111.9
	C. 3 pipes	no data	no data	no data	no data	no data	no data	56.9	56.9
	D. 4 pipes	no data	no data	no data	no data	no data	no data	95.4	95.4
	E. 5 pipes	no data	no data	no data	no data	no data	no data	29.0	29.0
	F. 6 pipe	no data	no data	no data	no data	no data	no data	31.5	31.5
	G. 7 pipes	no data	no data	no data	no data	no data	no data	16.8	16.8
	H. 8 pipes	no data	no data	no data	no data	no data	no data	8.4	8.4
	I. 9 pipes	no data	no data	no data	no data	no data	no data	9.7	9.7
	J. 10 pipes	no data	no data	no data	no data	no data	no data	2.9	2.9
	K. 11 pipes	no data	no data	no data	no data	no data	no data	4.1	4.1

	L. 12 pipes	no data	no data	no data	no data	no data	no data	2.0	2.0
	M. 13 pipes	no data	no data	no data	no data	no data	no data	0.8	0.8
	N. 14 pipes	no data	no data	no data	no data	no data	no data	0.7	0.7
	O. 15 pipes	no data	no data	no data	no data	no data	no data	1.2	1.2
	P. 17 pipes	no data	no data	no data	no data	no data	no data	1.0	1.0
	Q. 18 pipes	no data	no data	no data	no data	no data	no data	2.1	2.1
	R. 19 pipes	no data	no data	no data	no data	no data	no data	1.2	1.2
	S. 20 pipes	no data	no data	no data	no data	no data	no data	0.2	0.2
	T. 21 pipes	no data	no data	no data	no data	no data	no data	0.4	0.4
	U. 26 pipes	no data	no data	no data	no data	no data	no data	0.3	0.3
	TOTALS IN MILES							449.7	449.7
III. Length of Power Transmission Lines in Miles									
	A. Major transmission lines with towers	no data	no data	no data	no data	no data	no data	218.6	218.6
AREA MEASUREMENTS									
I. Gravel Roads									
	A. Roads	0.0	677.1	1002.3	2028.7	2448.4	2535.6	2744.7	2744.7
	B. Causeways	0.0	0.0	47.7	81.6	234.5	229.1	226.7	226.7
	SUB - TOTALS IN ACRES	0.0	677.1	1050.0	2110.3	2682.9	2764.7	2971.4	2971.4
II. Gravel or Paved Airstrips									
	A. Airstrip	6.1	135.8	251.6	287.3	313.3	313.0	287.4	287.4
III. Off Shore Gravel Pads / Islands									
	A. Exploration Islands	0.0	0.0	5.4	54.4	56.5	56.5	53.4	16.1
	B. Production Islands	0.0	0.0	0.0	0.0	76.4	92.4	101.1	101.1
	SUB - TOTALS IN ACRES	0.0	0.0	5.4	54.4	132.9	148.9	154.5	117.2
IV. Gravel Pads									
	A. Production pads/ Drill sites	0.0	276.4	647.3	2198.6	2916.9	3019.0	3126.1	3127.1
	B. Processing facility pads	0.0	74.4	389.8	692.2	873.8	889.5	917.4	917.4
	C. Support Pads (camps, power stations, etc.)	14.0	440.6	769.3	1340.1	1444.4	1470.3	1463.1	1463.1
	D. Exploration site - tundra covered by gravel pad	0.0	109.1	175.0	339.0	316.7	313.5	305.0	269.4
	SUB - TOTAL IN ACRES	14.0	900.5	1981.4	4569.9	5551.8	5692.3	5811.6	5777.0
	GRAVEL FOOTPRINT TOTALS IN ACRES	20.1	1713.4	3288.4	7021.9	8680.9	8918.9	9224.9	9153.0
V. Other Impacted Areas and Gravel Removed From Tundra									

	A. Exploration site - disturbed area around gravel pad	55.3	346.3	467.0	613.3	627.4	649.6	644.8	322.3
	B. Exploration airstrip - thin gravel / tundra scar	0.0	68.4	68.4	68.4	68.4	68.4	67.4	16.9
	C. Peat Roads	143.3	546.6	545.7	545.7	520.2	517.4	517.3	512.4
	D. Tractor trail / tundra scar	109.6	249.9	272.1	262.5	258.0	258.0	257.9	52.4
	E. Exp road - thin gravel / tundra scar	0.0	176.5	178.6	177.3	178.3	178.3	177.0	130.4
	F. Gravel pad removed, site in process of recovery	0.0	0.7	20.5	27.0	45.8	80.9	100.3	100.3
	G. Gravel pad removed, site is recovered	no data	no data	no data	no data	no data	no data	94.6	94.6
	OTHER IMPACT AREA TOTALS IN ACRES	308.2	1388.4	1552.3	1694.2	1698.1	1752.6	1764.7	1134.7
VI. Gravel Mines									
	A. In rivers	24.6	4732.0	4995.5	5011.1	5062.5	5060.5	5081.5	820.1
	B. In tundra	0.0	33.8	150.7	745.2	1178.7	1185.6	1282.7	994.8
	GRAVEL MINE TOTALS IN ACRES	24.6	4765.8	5146.2	5756.3	6241.2	6246.1	6364.2	1814.9
	IMPACT AREA TOTALS IN ACRES	352.9	7867.6	9986.9	14472.4	16620.2	16917.6	17353.8	12102.6

Table A-Aeromap-2. Oilfield infrastructure history through time for the North Slope west of Kalubik.

		1968	1973 cumulative	1977 cumulative	1983 cumulative	1988 cumulative	1994 cumulative	2001 cumulative	2001 current
POINT MEASUREMENTS									
	A. Number of gravel pads								
	1. Production pads/ Drill sites	0	0	0	0	0	0	5	5
	2. Processing facility pads	0	0	0	0	0	0	1	1
	3. Support Pads (power stations, camps, staging pads, etc.)	0	0	0	0	0	0	0	0
	4. Exploration sites	2	3	3	6	6	6	5	2
	5. Exploration Islands Offshore	0	0	0	0	0	0	0	0
	6. Production Islands offshore	0	0	0	0	0	0	0	0
	7. Airstrips	0	0	0	0	0	0	1	1
	8. Exploration airstrip - thin gravel / tundra scar	0	1	1	1	1	1	1	0
	B. Number of culverts	no data	no data	no data	no data	no data	no data	119	119
	C. Number of bridges	no data	no data	no data	no data	no data	no data	6	6
	D. Number of caribou crossings	no data	no data	no data	no data	no data	no data	0	0

	G. Number of Landfills	no data	no data	no data	no data	no data	no data	0	0
LENGTH MEASUREMENTS									
I. Length of Roads in Miles									
	A. Road	0.0	0.0	0.0	0.0	0.0	0.0	20.0	20.0
	B. Peat Road	29.6	29.6	29.6	29.6	29.6	29.6	29.6	29.6
	C. Causeway	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	D. Tractor trail / tundra scar	5.3	7.5	7.5	7.5	7.5	7.5	7.5	0.0
	E. Exp road - thin gravel / tundra scar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	TOTAL	34.9	37.1	37.1	37.1	37.1	37.1	57.1	49.6
II. Length of Pipeline Corridors in Miles									
	A. 1 pipe	no data	no data	no data	no data	no data	no data	28.7	28.7
	B. 2 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	C. 3 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	D. 4 pipes	no data	no data	no data	no data	no data	no data	21.6	21.6
	E. 5 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	F. 6 pipe	no data	no data	no data	no data	no data	no data	0.0	0.0
	G. 7 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	H. 8 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	I. 9 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	J. 10 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	K. 11 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	L. 12 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	M. 13 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	N. 14 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	O. 15 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	P. 17 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	Q. 18 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	R. 19 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	S. 20 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	T. 21 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	U. 26 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	TOTALS IN MILES							50.3	50.3
III. Length of Power Transmission Lines in Miles									
	A. Major transmission lines with towers	no data	no data	no data	no data	no data	no data	16.4	16.4
AREA MEASUREMENTS									
I. Gravel Roads									
	A. Roads	0.0	0.0	0.0	0.0	0.0	0.0	133.1	133.1

	B. Causeways	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	SUB - TOTALS IN ACRES	0.0	0.0	0.0	0.0	0.0	0.0	133.1	133.1
II. Gravel or Paved Airstrips									
	A. Airstrip	0.0	0.0	0.0	0.0	0.0	0.0	24.1	24.1
III. Off Shore Gravel Pads / Islands									
	A. Exploration Islands	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	B. Production Islands	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	SUB - TOTALS IN ACRES	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IV. Gravel Pads									
	A. Production pads/ Drill sites	0.0	0.0	0.0	0.0	0.0	0.0	53.5	53.5
	B. Processing facility pads	0.0	0.0	0.0	0.0	0.0	0.0	22.8	22.8
	C. Support Pads (camps, power stations, etc.)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	D. Exploration site - tundra covered by gravel pad	0.0	0.0	0.0	7.0	7.0	7.0	4.4	4.4
	SUB - TOTAL IN ACRES	0.0	0.0	0.0	7.0	7.0	7.0	80.7	80.7
	GRAVEL FOOTPRINT TOTALS IN ACRES	0.0	0.0	0.0	7.0	7.0	7.0	237.9	237.9
V. Other Impacted Areas and Gravel Removed From Tundra									
	A. Exploration site - disturbed area around gravel pad	23.2	44.1	44.1	46.3	46.3	53.4	45.8	16.0
	B. Exploration airstrip - thin gravel / tundra scar	0.0	22.4	22.4	22.4	22.4	22.4	22.4	0.0
	C. Peat Roads	143.3	143.3	143.3	143.3	143.3	143.3	143.3	143.3
	D. Tractor trail / tundra scar	25.7	36.4	36.4	36.4	36.4	36.4	36.4	0.0
	E. Exp road - thin gravel / tundra scar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	F. Gravel pad removed, site in process of recovery	0.0	0.0	0.0	0.0	0.0	0.0	3.2	3.2
	G. Gravel pad removed, site is recovered	no data	no data	no data	no data	no data	no data	0.0	0.0
	OTHER IMPACT AREA TOTALS IN ACRES	192.2	246.2	246.2	248.4	248.4	255.5	251.1	162.5
VI. Gravel Mines									
	A. In rivers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	B. In tundra	0.0	0.0	0.0	0.0	0.0	0.0	49.9	49.9
	GRAVEL MINE TOTALS IN ACRES	0.0	0.0	0.0	0.0	0.0	0.0	49.9	49.9

	IMPACT AREA TOTALS IN ACRES	192.2	246.2	246.2	255.4	255.4	262.5	538.9	450.3

Table A-Aeromap-3. Oilfield infrastructure history through time for the North Slope between Kalubik and Kuparuk.

		1968	1973 cumulative	1977 cumulative	1983 cumulative	1988 cumulative	1994 cumulative	2001 cumulative	2001 current
POINT MEASUREMENTS									
	A. Number of gravel pads								
	1. Production pads/ Drill sites	0	0	0	28	53	58	62	62
	2. Processing facility pads	0	0	0	3	5	5	5	5
	3. Support Pads (power stations, camps, staging pads, etc.)	0	1	1	5	7	9	10	10
	4. Exploration sites	0	17	24	42	45	45	45	39
	5. Exploration Islands Offshore	0	0	0	0	1	1	1	0
	6. Production Islands offshore	0	0	0	0	0	0	0	0
	7. Airstrips	0	3	4	5	5	5	5	5
	8. Exploration airstrip - thin gravel / tundra scar	0	0	0	0	0	0	0	0
	B. Number of culverts	no data	no data	no data	no data	no data	no data	487	487
	C. Number of bridges	no data	no data	no data	no data	no data	no data	3	3
	D. Number of caribou crossings	no data	no data	no data	no data	no data	no data	12	12
	G. Number of Landfills	no data	no data	no data	no data	no data	no data	0	0
LENGTH MEASUREMENTS									
I. Length of Roads in Miles									
	A. Road	0.0	9.1	15.0	104.0	145.4	153.9	161.5	161.5
	B. Peat Road	0.0	25.4	25.4	25.3	25.0	25.0	25.0	25.0
	C. Causeway	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	D. Tractor trail / tundra scar	0.0	32.1	32.0	31.0	30.4	30.4	30.3	9.5
	E. Exp road - thin gravel / tundra scar	0.0	4.6	4.6	4.6	4.6	4.6	4.4	4.4
	TOTAL	0.0	71.2	77.0	164.9	205.4	213.9	221.2	200.4
II. Length of Pipeline Corridors in Miles									
	A. 1 pipe	no data	no data	no data	no data	no data	no data	10.5	10.5
	B. 2 pipes	no data	no data	no data	no data	no data	no data	38.7	38.7
	C. 3 pipes	no data	no data	no data	no data	no data	no data	33.8	33.8
	D. 4 pipes	no data	no data	no data	no data	no data	no data	51.4	51.4
	E. 5 pipes	no data	no data	no data	no data	no data	no data	13.4	13.4
	F. 6 pipe	no data	no data	no data	no data	no data	no data	12.3	12.3

	G. 7 pipes	no data	no data	no data	no data	no data	no data	3.6	3.6
	H. 8 pipes	no data	no data	no data	no data	no data	no data	3.7	3.7
	I. 9 pipes	no data	no data	no data	no data	no data	no data	0.9	0.9
	J. 10 pipes	no data	no data	no data	no data	no data	no data	0.2	0.2
	K. 11 pipes	no data	no data	no data	no data	no data	no data	1.6	1.6
	L. 12 pipes	no data	no data	no data	no data	no data	no data	0.7	0.7
	M. 13 pipes	no data	no data	no data	no data	no data	no data	0.6	0.6
	N. 14 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	O. 15 pipes	no data	no data	no data	no data	no data	no data	0.7	0.7
	P. 17 pipes	no data	no data	no data	no data	no data	no data	0.4	0.4
	Q. 18 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	R. 19 pipes	no data	no data	no data	no data	no data	no data	0.9	0.9
	S. 20 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	T. 21 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	U. 26 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	TOTALS IN MILES							173.4	173.4
III. Length of Power Transmission Lines in Miles									
	A. Major transmission lines with towers	no data	no data	no data	no data	no data	no data	122.7	122.7
AREA MEASUREMENTS									
I. Gravel Roads									
	A. Roads	0.0	62.6	94.8	692.7	952.9	1015.3	1066.3	1066.3
	B. Causeways	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	SUB - TOTALS IN ACRES	0.0	62.6	94.8	692.7	952.9	1015.3	1066.3	1066.3
II. Gravel or Paved Airstrips									
	A. Airstrip	0.0	15.3	31.2	65.2	65.2	65.2	47.6	47.6
III. Off Shore Gravel Pads / Islands									
	A. Exploration Islands	0.0	0.0	0.0	0.0	3.5	3.5	3.5	0.0
	B. Production Islands	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	SUB - TOTALS IN ACRES	0.0	0.0	0.0	0.0	3.5	3.5	3.5	0.0
IV. Gravel Pads									
	A. Production pads/ Drill sites	0.0	0.0	0.0	484.5	976.9	1028.1	1075.5	1075.5
	B. Processing facility pads	0.0	0.0	0.0	187.1	248.2	248.2	248.2	248.2
	C. Support Pads (camps, power stations, etc.)	0.0	8.7	8.7	136.0	172.2	175.1	175.7	175.7
	D. Exploration site - tundra covered by gravel pad	0.0	55.6	73.2	123.4	121.1	121.1	121.1	107.2
	SUB - TOTAL IN ACRES	0.0	64.3	81.9	931.0	1518.4	1572.5	1620.5	1606.6

	GRAVEL FOOTPRINT TOTALS IN ACRES	0.0	142.2	207.9	1688.9	2540.0	2656.5	2737.9	2720.5
V. Other Impacted Areas and Gravel Removed From Tundra									
	A. Exploration site - disturbed area around gravel pad	0.0	129.2	161.4	228.8	241.1	241.0	241.0	114.2
	B. Exploration airstrip - thin gravel / tundra scar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	C. Peat Roads	0.0	132.9	132.9	132.7	131.3	131.2	131.2	131.0
	D. Tractor trail / tundra scar	0.0	130.4	129.8	130.5	127.6	127.6	127.5	35.6
	E. Exp road - thin gravel / tundra scar	0.0	16.6	16.6	16.6	16.6	16.6	15.5	15.5
	F. Gravel pad removed, site in process of recovery	0.0	0.0	0.0	0.0	10.5	20.0	24.9	24.9
	G. Gravel pad removed, site is recovered	no data	no data	no data	no data	no data	no data	22.6	22.6
	OTHER IMPACT AREA TOTALS IN ACRES	0.0	409.1	440.7	508.6	527.1	536.4	540.1	321.2
VI. Gravel Mines									
	A. In rivers	0.0	451.8	451.9	476.7	476.8	476.8	476.8	9.1
	B. In tundra	0.0	0.0	0.0	362.3	605.7	612.6	627.3	465.7
	GRAVEL MINE TOTALS IN ACRES	0.0	451.8	451.9	839.0	1082.5	1089.4	1104.1	474.8
	IMPACT AREA TOTALS IN ACRES	0.0	1003.1	1100.5	3036.5	4149.6	4282.3	4382.1	3516.5

Table A-Aeromap-4. Oilfield infrastructure history through time for the North Slope from Kuparuk to Foggy Island.

		1968	1973 cumulative	1977 cumulative	1983 cumulative	1988 cumulative	1994 cumulative	2001 cumulative	2001 current
POINT MEASUREMENTS									
	A. Number of gravel pads								
	1. Production pads/ Drill sites	0	16	22	34	42	46	47	47
	2. Processing facility pads	0	6	10	11	13	13	13	13
	3. Support Pads (power stations, camps, staging pads, etc.)	1	35	61	92	100	103	103	103
	4. Exploration sites	1	19	30	39	37	36	36	34
	5. Exploration Islands Offshore	0	0	2	10	10	10	10	4
	6. Production Islands offshore	0	0	0	0	2	3	4	4
	7. Airstrips	1	7	8	8	8	8	7	7

	8. Exploration airstrip - thin gravel / tundra scar	0	3	3	3	3	3	3	2
	B. Number of culverts	no data	no data	no data	no data	no data	no data	772	772
	C. Number of bridges	no data	no data	no data	no data	no data	no data	8	8
	D. Number of caribou crossings	no data	no data	no data	no data	no data	no data	38	38
	G. Number of Landfills	no data	no data	no data	no data	no data	no data	1	1
LENGTH MEASUREMENTS									
I. Length of Roads in Miles									
	A. Road	0.0	90.5	123.4	189.8	211.9	215.7	214.9	214.9
	B. Peat Road	0.0	45.5	45.4	45.4	41.5	41.0	41.0	40.1
	C. Causeway	0.0	0.0	1.9	2.7	7.5	7.5	7.5	7.5
	D. Tractor trail / tundra scar	13.7	14.1	19.0	18.6	18.6	18.6	18.6	4.3
	E. Exp road - thin gravel / tundra scar	0.0	31.2	31.8	31.5	31.5	31.5	31.6	23.2
	TOTAL	13.7	181.3	221.5	288.0	311.0	314.3	313.6	290.0
II. Length of Pipeline Corridors in Miles									
	A. 1 pipe	no data	no data	no data	no data	no data	no data	34.0	34.0
	B. 2 pipes	no data	no data	no data	no data	no data	no data	55.8	55.8
	C. 3 pipes	no data	no data	no data	no data	no data	no data	23.1	23.1
	D. 4 pipes	no data	no data	no data	no data	no data	no data	22.4	22.4
	E. 5 pipes	no data	no data	no data	no data	no data	no data	15.6	15.6
	F. 6 pipe	no data	no data	no data	no data	no data	no data	19.2	19.2
	G. 7 pipes	no data	no data	no data	no data	no data	no data	13.2	13.2
	H. 8 pipes	no data	no data	no data	no data	no data	no data	4.7	4.7
	I. 9 pipes	no data	no data	no data	no data	no data	no data	8.8	8.8
	J. 10 pipes	no data	no data	no data	no data	no data	no data	2.7	2.7
	K. 11 pipes	no data	no data	no data	no data	no data	no data	2.5	2.5
	L. 12 pipes	no data	no data	no data	no data	no data	no data	1.3	1.3
	M. 13 pipes	no data	no data	no data	no data	no data	no data	0.2	0.2
	N. 14 pipes	no data	no data	no data	no data	no data	no data	0.7	0.7
	O. 15 pipes	no data	no data	no data	no data	no data	no data	0.5	0.5
	P. 17 pipes	no data	no data	no data	no data	no data	no data	0.6	0.6
	Q. 18 pipes	no data	no data	no data	no data	no data	no data	2.1	2.1
	R. 19 pipes	no data	no data	no data	no data	no data	no data	0.3	0.3
	S. 20 pipes	no data	no data	no data	no data	no data	no data	0.2	0.2
	T. 21 pipes	no data	no data	no data	no data	no data	no data	0.4	0.4
	U. 26 pipes	no data	no data	no data	no data	no data	no data	0.3	0.3
	TOTALS IN MILES							208.6	208.6
III. Length of Power Transmission Lines in Miles									

	A. Major transmission lines with towers	no data	no data	no data	no data	no data	no data	79.5	79.5
AREA MEASUREMENTS									
I. Gravel Roads									
	A. Roads	0.0	611.7	904.7	1333.2	1492.7	1517.5	1518.8	1518.8
	B. Causeways	0.0	0.0	47.7	81.6	234.5	229.1	222.7	222.7
	SUB - TOTALS IN ACRES	0.0	611.7	952.4	1414.8	1727.2	1746.6	1741.5	1741.5
II. Gravel or Paved Airstrips									
	A. Airstrip	6.1	114.0	205.5	207.2	233.2	232.9	193.3	193.3
III. Off Shore Gravel Pads / Islands									
	A. Exploration Islands	0.0	0.0	5.4	43.4	42.0	42.0	38.9	10.9
	B. Production Islands	0.0	0.0	0.0	0.0	76.4	92.4	101.1	101.1
	SUB - TOTALS IN ACRES	0.0	0.0	5.4	43.4	118.4	134.4	140.0	112.0
IV. Gravel Pads									
	A. Production pads/ Drill sites	0.0	276.4	647.3	1714.1	1940.0	1990.9	1975.9	1976.9
	B. Processing facility pads	0.0	74.4	389.8	505.1	625.6	641.3	645.1	645.1
	C. Support Pads (camps, power stations, etc.)	14.0	431.9	753.1	1196.6	1264.7	1287.7	1273.7	1273.7
	D. Exploration site - tundra covered by gravel pad	0.0	46.5	84.9	135.9	115.9	106.3	100.4	92.6
	SUB - TOTAL IN ACRES	14.0	829.2	1875.1	3551.7	3946.2	4026.2	3995.1	3988.3
	GRAVEL FOOTPRINT TOTALS IN ACRES	20.1	1554.9	3038.4	5217.1	6025.0	6140.1	6069.9	6035.1
V. Other Impacted Areas and Gravel Removed From Tundra									
	A. Exploration site - disturbed area around gravel pad	32.1	149.5	202.3	212.9	214.7	219.6	228.5	107.7
	B. Exploration airstrip - thin gravel / tundra scar	0.0	46.0	46.0	46.0	46.0	46.0	45.0	16.9
	C. Peat Roads	0.0	269.6	268.7	268.9	244.8	242.1	242.1	237.4
	D. Tractor trail / tundra scar	83.9	83.1	105.9	95.6	94.0	94.0	94.0	16.8
	E. Exp road - thin gravel / tundra scar	0.0	159.9	162.0	160.7	161.7	161.7	161.5	114.9
	F. Gravel pad removed, site in process of recovery	0.0	0.7	20.5	27.0	35.3	60.9	72.2	72.2
	G. Gravel pad removed, site is recovered	no data	no data	no data	no data	no data	no data	72.0	72.0
	OTHER IMPACT AREA TOTALS IN ACRES	116.0	708.8	805.4	811.1	796.5	824.3	843.3	565.9
VI. Gravel Mines									

	A. In rivers	24.6	4280.2	4543.6	4534.4	4585.7	4583.7	4604.7	811.0
	B. In tundra	0.0	0.0	116.9	326.9	517.0	517.0	517.0	471.8
	GRAVEL MINE TOTALS IN ACRES	24.6	4280.2	4660.5	4861.3	5102.7	5100.7	5121.7	1282.8
	IMPACT AREA TOTALS IN ACRES	160.7	6543.9	8504.3	10889.5	11924.2	12065.1	12034.9	7883.8

Table A-Aeromap-5. Oilfield infrastructure through time for the North Slope east of Foggy Island.

		1968	1973 cumulative	1977 cumulative	1983 cumulative	1988 cumulative	1994 cumulative	2001 cumulative	2001 current
POINT MEASUREMENTS									
	A. Number of gravel pads								
	1. Production pads/ Drill sites	0	0	0	0	0	0	1	1
	2. Processing facility pads	0	0	0	0	0	0	1	1
	3. Support Pads (power stations, camps, staging pads, etc.)	0	0	1	1	1	1	2	2
	4. Exploration sites	0	3	6	16	16	19	17	16
	5. Exploration Islands Offshore	0	0	0	2	2	2	2	1
	6. Production Islands offshore	0	0	0	0	0	0	0	0
	7. Airstrips	0	1	3	3	3	3	3	3
	8. Exploration airstrip - thin gravel / tundra scar	0	0	0	0	0	0	0	0
	B. Number of culverts	no data	no data	no data	no data	no data	no data	17	17
	C. Number of bridges	no data	no data	no data	no data	no data	no data	0	0
	D. Number of caribou crossings	no data	no data	no data	no data	no data	no data	0	0
	G. Number of Landfills	no data	no data	no data	no data	no data	no data	0	0
LENGTH MEASUREMENTS									
I. Length of Roads in Miles									
	A. Road	0.0	0.4	0.4	0.4	0.4	0.4	3.7	3.7
	B. Peat Road	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	C. Causeway	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2
	D. Tractor trail / tundra scar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	E. Exp road - thin gravel / tundra scar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	TOTAL	0.0	0.6	0.6	0.6	0.6	0.6	4.1	4.1
II. Length of Pipeline Corridors in Miles									
	A. 1 pipe	no data	no data	no data	no data	no data	no data	0.0	0.0
	B. 2 pipes	no data	no data	no data	no data	no data	no data	17.4	17.4
	C. 3 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0

	D. 4 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	E. 5 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	F. 6 pipe	no data	no data	no data	no data	no data	no data	0.0	0.0
	G. 7 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	H. 8 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	I. 9 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	J. 10 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	K. 11 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	L. 12 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	M. 13 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	N. 14 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	O. 15 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	P. 17 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	Q. 18 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	R. 19 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	S. 20 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	T. 21 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	U. 26 pipes	no data	no data	no data	no data	no data	no data	0.0	0.0
	TOTALS IN MILES							17.4	17.4
III. Length of Power Transmission Lines in Miles									
	A. Major transmission lines with towers	no data	no data	no data	no data	no data	no data	0	0
AREA MEASUREMENTS									
I. Gravel Roads									
	A. Roads	0.0	2.8	2.8	2.8	2.8	2.8	26.5	26.5
	B. Causeways	0.0	0.0	0.0	0.0	0.0	0.0	4.0	4.0
	SUB - TOTALS IN ACRES	0.0	2.8	2.8	2.8	2.8	2.8	30.5	30.5
II. Gravel or Paved Airstrips									
	A. Airstrip	0.0	6.5	14.9	14.9	14.9	14.9	22.4	22.4
III. Off Shore Gravel Pads / Islands									
	A. Exploration Islands	0.0	0.0	0.0	11.0	11.0	11.0	11.0	5.2
	B. Production Islands	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	SUB - TOTALS IN ACRES	0.0	0.0	0.0	11.0	11.0	11.0	11.0	5.2
IV. Gravel Pads									
	A. Production pads/ Drill sites	0.0	0.0	0.0	0.0	0.0	0.0	21.2	21.2
	B. Processing facility pads	0.0	0.0	0.0	0.0	0.0	0.0	1.3	1.3
	C. Support Pads (camps, power stations, etc.)	0.0	0.0	7.5	7.5	7.5	7.5	13.7	13.7

	D. Exploration site - tundra covered by gravel pad	0.0	7.0	16.9	72.7	72.7	79.1	79.1	65.2
	SUB - TOTAL IN ACRES	0.0	7.0	24.4	80.2	80.2	86.6	115.3	101.4
	GRAVEL FOOTPRINT TOTALS IN ACRES	0.0	16.3	42.1	108.9	108.9	115.3	179.2	159.5
V. Other Impacted Areas and Gravel Removed From Tundra									
	A. Exploration site - disturbed area around gravel pad	0.0	23.5	59.2	125.3	125.3	135.6	129.5	84.4
	B. Exploration airstrip - thin gravel / tundra scar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	C. Peat Roads	0.0	0.8	0.8	0.8	0.8	0.8	0.7	0.7
	D. Tractor trail / tundra scar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	E. Exp road - thin gravel / tundra scar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	F. Gravel pad removed, site in process of recovery	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	G. Gravel pad removed, site is recovered	no data	no data	no data	no data	no data	no data	0.0	0.0
	OTHER IMPACT AREA TOTALS IN ACRES	0.0	24.3	60.0	126.1	126.1	136.4	130.2	85.1
VI. Gravel Mines									
	A. In rivers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	B. In tundra	0.0	33.8	33.8	56.0	56.0	56.0	88.5	7.4
	GRAVEL MINE TOTALS IN ACRES	0.0	33.8	33.8	56.0	56.0	56.0	88.5	7.4
	IMPACT AREA TOTALS IN ACRES	0.0	74.4	135.9	291.0	291.0	307.7	397.9	252.0

Appendix F:

Oil Spills

Large oil spills are infrequent events, usually in different locations. They occur, they are cleaned up as much as possible, some restoration may be attempted, and over time, natural recovery may occur. Unless spills occur repeatedly in a location, or are very large, their effects usually do not accumulate. On the North Slope, there have been no major offshore oil spills or large spills—greater than 1,000 bbl (42,000 gallons) according to the Minerals Management Service (MMS) definition—associated with exploration and production. Three large spills from the Trans Alaska Pipeline have occurred on the North Slope (Table F-1). There have been many small spills onshore, however, and the potential for future spills offshore (large and small) exists. This appendix describes the history of spills, spill prevention efforts, response to spills, and the fate and effects of oil spilled on the North Slope.

Table F-1 Ten largest crude oil spills from TAPS: Pump Station 1 to Atigun Pass 1977-2000 (Modified from Maxim and Niebo 2001b).

Number	Date	Volume (bbl)	Description
1	19 Jul 77	1800	Heavy equipment accident caused leak at checkvalve7, milepoint 27
2	1 Jan 81	1500	Check valve 23 malfunctiond and leaked when a drain connection failed.
3	10 Jun 79	1500	Pipe settlement at Atigun Pass caused a leak.
4	16 Aug 77	30	Sump at Pump Station 1 overflowed.
5	24 Nov 94	18	Valve left open after routine maintenance.
6	17 May 84	11	Broken drain plug at the Pump Station 3 tank farm.
7	28 Oct 80	6	Valve malfunction at Pump Station 2.
8	4 May 84	5	O-ring seal failed at Pump Station 4 manifold building.
9	23 Aug 89	5	Discharge relief valve stem failed, Pump Station 2
10	5 Dec 81	5	Check valve leaked, metering building at Pump Station 1

Source: TAPS Owners 2001.

OIL SPILLS

History of North Slope Oil Spills

Spills are unintentional, accidental releases of crude oil or petroleum products. They have been analysed statistically for the Trans Alaska Pipeline System (TAPS), divided into four components (Maxim and Niebo 2001b):

1. Exploration and Production Facilities—well pads, flowlines, gathering centers, base operation centers, power stations, and pipelines which feed into TAPS.
2. TAPS—pipeline, pump stations, storage tanks and associated facilities.
3. Valdez Marine Terminal—storage tanks, pumps, connecting pipes, and tanker berths.
4. Marine Transport—tankers carrying crude oil to destination ports.

Here we focus on North Slope exploration and production facilities, and on TAPS pipeline from Pump Station 1 to Atigun Pass.

Sources of Spills from North Slope Facilities and the Trans Alaska Pipeline to Atigun Pass

Oil is produced from wells on gravel pads onshore or offshore on islands. In-field pipelines (flowlines) carry multiphase slurries containing oil, gas, and water from wellhead to CPFs (Central Processing Facilities), sometimes called flowstations. A CPF is the operational center of the production activities. It typically includes processing equipment, storage tanks for fuel and water, power generators, maintenance facilities, living quarters, and communications facilities. The processing equipment includes three-phase separators. Oil, gas, and water are produced in varying proportions from each well. Gas conditioning equipment removes natural gas liquids from produced gas. Pipeline gathering and pressure regulation systems and well monitoring and control systems are also part of the CPF. Oil is filtered to remove any sand or grit. After processing the oil (now called sales oil) is routed through a sales meter and enters a feeder pipeline (also called sales-oil pipeline) for delivery to a larger diameter pipeline to Pump Station 1 of the Trans Alaska Pipeline.

Natural gas extracted during processing is further processed to remove liquids, then compressed and reinjected into the reservoir through service wells. Water is chemically treated and also reinjected into the reservoir. Reinjection of water and natural gas increases oil recovery by maintaining reservoir pressure.

Pipelines that carry water, gas, crude oil and diesel vary in diameter, and are normally installed above ground on vertical support members. Above-ground pipelines are easier to monitor, repair, and reconfigure when necessary. Offshore pipelines are buried until they reach shore where they join the pipeline system. Spills can potentially occur from pipelines, pump stations, support facilities such as aboveground and underground storage tanks, and support facilities such as tanker trucks. Spills can occur at any place where crude oil or products are handled, stored, used, or transported.

Spill Statistics

North Slope

Spills have been reported and recorded over the years of operation of the oilfields and TAPS. The information discussed here is primarily from the analysis recently prepared for the TAPS Owners (2001) in support of their application for right-of-way renewal. The period covered is from 1977, when the first oil flowed through TAPS, through 1999. The data were compiled by IT Corporation from original source documents with minor adjustments and corrections made more recently by Niebo (2001; Niebo, personal communication 2001), and

Maxim and Niebo (2001). Table F-2 shows spills associated with exploration and production activities on the North Slope; Table F-3 shows spills associated with TAPS pipeline operations from Pump Station 1 to Atigun Pass. Over the 23-year period, there was an average of 70 crude oil and 234 products spills per year associated with North Slope operations and the North Slope segment of TAPS operations. The volume spilled amounts to a yearly average of 523 bbl (21,966 gallons) of crude oil and 278 bbl (11,676 gallons) of products (Niebo, personal communication, 2001).

Table F-2 Numbers and volumes of North Slope crude oil and petroleum products spills. (Modified from Neibo 2001b). Spills from exploration and production activities on the North Slope.

Year	Crude oil		Petroleum products	
	number	volume (bbls)	number	Volume (bbls)
1977	12	75.58	22	163.68
1978	12	47.62	20	82.27
1979	20	101.64	16	25.44
1980	22	50.12	46	236.24
1981	54	57.88	181	1,004.93
1982	59	158.81	91	393.45
1983	62	105.76	120	413.15
1984	48	358.60	23	34.00
1985	91	535.43	168	363.17
1986	91	164.67	145	410.40
1987	97	256.64	137	102.10
1988	129	270.70	312	240.94
1989	163	1,790.05	408	364.64
1990	102	223.50	359	234.85
1991	140	65.56	445	324.86
1992	70	34.80	259	81.80
1993	61	2,230.65	209	65.21
1994	51	298.76	159	54.23
1995	39	33.33	132	115.87
1996	52	46.26	141	97.31
1997	39	97.89	123	321.65
1998	44	118.49	124	40.56
1999	27	6.16	258	49.07
Totals	**1.485**	**7,128.91**	**3,898**	**5,219.81**

Reported volumes of North Slope spills vary by more than six orders of magnitude, from 0.006 to 925 bbl (0.336 to 38,850 gallons). The statistical distribution of the volumes of crude and product spills on the North Slope are approximately lognormal. Relatively small spills are frequent, but there is a long "tail" to the distribution, with total volume dominated by the relatively few larger spills (Maxim and Niebo 2001b). This is typically plotted using a Lorenz diagram (Figure F-1) that graphs the fraction of the spill volume (on the vertical axis) versus the fraction of the number of spills (on the horizontal axis). First, spill data are sorted in ascending order of spill volume. Next the cumulative fraction of the total volume spilled (vertical axis) is plotted as a function of the cumulative fraction of the number of spills (horizontal axis). If all spills were exactly the same size, the fraction of the spill volume would correspond exactly to the fraction of the number of spills. The 45 degree line "AB" depicts this situation. If some spills

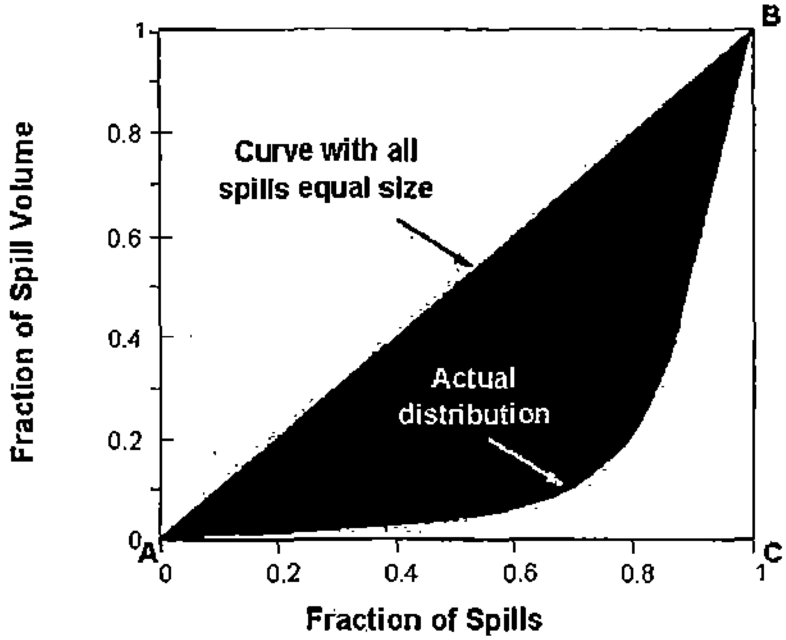


FIGURE F-1. Hypothetical Lorenz diagram. Source: reprinted with permission from Maxim and Niebo 2001.

are larger than others then the fraction of the spilled volume will be less than the fraction of the number of spills, as shown in the curve "AB" beneath the 45 degree line. The area between the curve and the straight line (shaded) illustrates the degree of inequality in spill size distribution. Dividing the shaded area by the area of the triangle "ABC" provides a normalized index or coefficient, denoted L, of the variability in spill volumes. L ranges from 0 (all spills the same size) to 1 (Maxim and Niebo 2001b).

Table F-3 Numbers and volumes of crude oil and petroleum products spills (Modified from Neibo 2001b). Spills associated TAPS from Pump Station 1 to Atigun Pass.

Year	Crude oil		Petroleum products	
	number	volume (bbls)	number	Volume (bbls)
1977	9	1,831.07	771	162.58
1978	3	5.00	17	26.06
1979	7	1,502.67	24	159.78
1980	3	6.28	38	9.14
1981	6	1,505.24	28	13.14
1982	8	4.21	55	93.22
1983	4	2.08	14	4.88
1984	8	16.24	14	12.86
1985	4	0.10	11	4.81
1986	1	0.71	14	90.10
1987	0	0	4	5.39
1988	5	0.24	17	207.21
1989	3	5.72	22	12.30
1990	9	1.10	49	51.16
1991	9	1.92	114	24.30
1992	10	0.42	48	232.47
1993	11	2.66	46	25.61
1994	11	20.84	82	5.16
1995	1	0.71	31	7.12
1996	1	0.07	15	2.68
1997	2	0.12	29	6.19
1998	0	0	18	23.16
1999	2	0.26	12	3.68
Totals	**117**	**4,907.67**	**1,473**	**1,183.00**

The diagram in Figure F-1 is hypothetical; its purpose is to illustrate the concept. The actual curves for exploration and production spills are more extreme. Figure F-2 is a Lorenz plot for North Slope crude oil and products spills over the period 1977-1999. There is substantial curvature in these plots, and the computed Lorenz coefficients are 0.911 and 0.883 for crude and products spills, respectively (Maxim and Niebo 2001b). Thus, a few relatively large spills account for most of the spill volume, as is typical of most oilfields (e.g., Smith et al. 1982, BLM/MMS 1998, MMS 2001). Fifty percent of North Slope crude spills were less than or equal to 0.238 bbl (9.996 gallons). Fifty percent of the product spills were less than or equal to 0.119 bbl (4.998 gallons). The smallest 90% of crude spills accounted for approximately 13% of the total volume spilled in this segment and the smallest 95% of the spills accounted for approximately 20% of the spilled volume. The corresponding percentages for products spills were 16% and 25%, respectively.

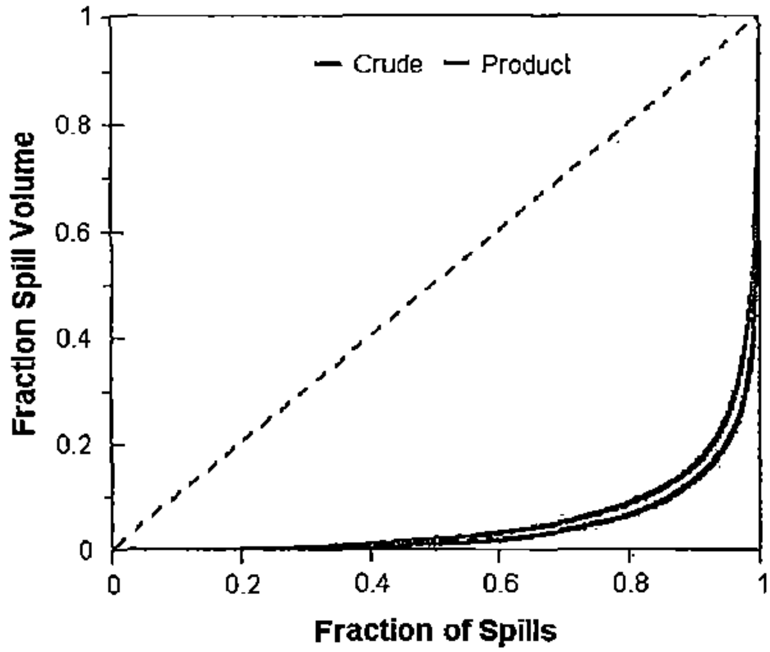


FIGURE F-2. Actual Lorenz diagram for crude oil and products spills associated with exploration and production activities on the North Slope. Source: reprinted with permission from Maxim and Niebo 2001.

From an environmental standpoint, small spills are generally less significant than large spills because they are typically contained and cleaned up at the site of the spill (e.g., drill pad), and therefore, are less likely to cause significant adverse environmental effects. Contaminated gravel cannot be reused before it has been cleaned; current regulations require such cleanup, or disposal, of contaminated gravel. Small spills also account for only a small portion of the total volume spilled.

TAPS: Pump Station 1 to Atigun Pass

Maxim and Niebo (2001) analysed spills along the Trans-Alaska Pipeline using the TAPS (2001) oil spill database. There are 10,588 spill records in the entire database. The North Slope segment from Pump Station 1 to Atigun Pass contains 3,244 records; 232 are crude oil spills and 3,012 are products spills. To identify the spills from Atigun Pass north, spill records were identified by mile marker number on the pipeline or Dalton Highway, pump station number, check valve number, material site number, access road number or landmark name. Using these criteria, 28 spill records did not contain enough information to be positively located north or south of Atigun Pass. Four of them were crude oil spills totalling 303 bbl (12,726 gallons). One spill was 300 bbl (12,600 gallons). The other 24 were products spills totalling 147 bbl (6,174 gallons). These questionable records were not considered part of North Slope segment of TAPS (Maxim and Niebo 2001b).

During the period from 1977 to 1999, 1,590 spills occurred along the pipeline segment from Pump Station 1 to Atigun Pass. Of these, 117 were crude oil spills, and 1,473 were products spills. The total volume of crude oil spilled over the 23 year period was 4,908 bbl (206,136 gallons), and 1,183 bbl (49,686 gallons) of petroleum products, an annual average of 69 spills per year with an annual volume of 265 bbl (11,130 gallons) spilled. For comparison, operation of the entire TAPS during the same period resulted in 3,244 crude oil and products spills totalling 32,092 bbl (1,347,864 gallons), an annual average of 141 spills with an annual volume of 1,395 bbl (58,590 gallons). Spills north of Atigun Pass represent approximately 19 percent of all materials spilled along TAPS. The volumetric spill rate (VSR), i.e., barrels spilled per million barrels of throughput, was 0.477 for the period (Maxim and Niebo 2001b). Figure F-3 shows the annual VSR for this TAPS segment. The spill rate was highest during the early years of the pipeline's operation, dropped in the early 1980s, and has remained relatively constant since then.

Spill records in TAPS segment 1 vary in volume by more than eight orders of magnitude, from 0.00001 bbl (0.00042 gallons) to 1,800 bbl (75,600 gallons). The total spill volume is dominated by a few relatively large spills (Figure F-4). Fifty percent of both crude oil and products spills in this pipeline segment were less than 0.07143 bbl (3 gallons). The smallest 90 % of crude oil spills accounted for approximately 0.5 % of the total volume spilled, and the smallest 95 % of crude oil spills accounted for approximately 1.2 % of the total volume. The corresponding percentages for products spills were 9 and 11 %, respectively (Maxim and Niebo 2001b).

Larger Volume Spills History

Because most oil is released in a few large spills, we highlight the highest volume crude oil and products spills that have occurred over the operating history of the fields, including causes, effects, corrective actions and countermeasures.

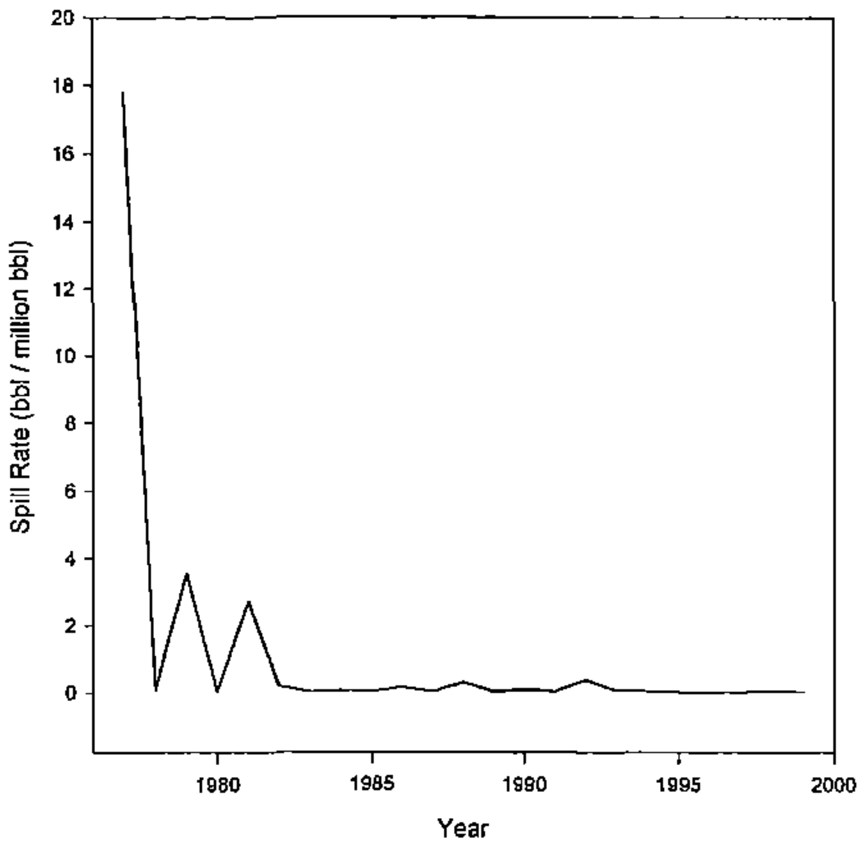


FIGURE F-3. Volumetric Spill Rate (VSR) for crude oil and products spills associated with the Trans Alaska Pipeline System from Pumpstation 1 to Atigun Pass. Source: reprinted with permission from Maxim and Niebo 2001.

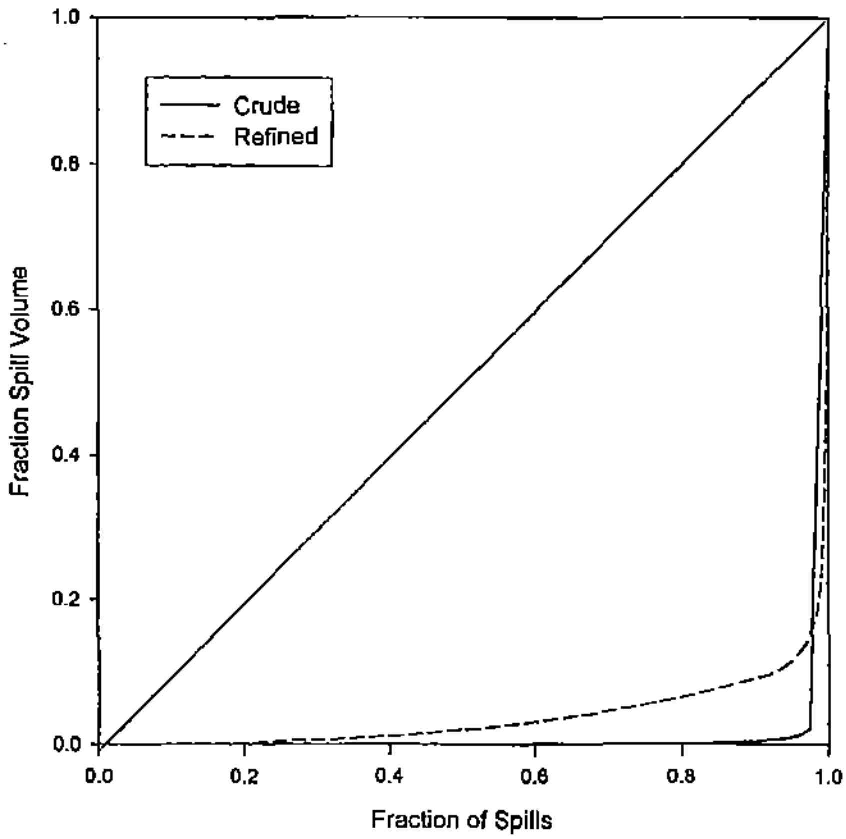


FIGURE F-4. Lorenz diagram of crude oil and products spills associated with the Trans Alaska Pipeline System from Pumpstation 1 to Atigun Pass. Source: reprinted with permission from Maxim and Niebo 2001.

Table F-4 is a list of the 10 largest North Slope crude oil spills (120 to 925 bbl, or 5,040 to 38,850 gallons) during the 1977 to 1999 period. Causes (BLM/MMS 1998, MMS 2001, Parametrix 1997) include leaks from or damage to storage tanks, faulty valves and gauges, faulty connections, vent discharges, ruptured lines, seal failures, explosions, various human errors (e.g., tank overfill, failure to ensure connections).

Table F-4 Ten largest crude oil spills on the North Slope 1977-2000 (Modified from Maxim and Niebo 2001b).

Number	Date	Volume (bbl)	Description
1	28 Jul 89	925	Oil reserve tank overflowed into reserve pit. Alarm system failed.
2	26 Sep 93	650	Pump failure caused tank overflow. Inlet valve was closed and outlet valve opened, allowing oil to spill into a containment dike. High winds carried some oil mist to snow outside containment dike.
3	30 dec 93	375	Wind-induced vibration caused a flowline to crack. Crude oil sprayed from crack. High winds carried some oil away from the pad.
4	10 Jun 93	300	High-level alarm failed on drum.
5	24 Dec 93	180	Level monitor, high-level alarm, and automatic shutoff devices froze on a tank, allowing oil to flow out of the overflow line. Crude oil flowed into the lined area surrounding the tank.
6	8 Nov 89	180	Break in temporary flowline caused by internal erosion. Crude oil was released onto gravel pad.
7	10 Dec 90	176	Explosion and fire caused by fluid leaking from a vacuum truck. Oil was released onto pad.
8	15 Nov 85	175	Faulty valve allowed crude oil to be released into a holding pit.
9	5 Nov 84	125	Bleeder valve was stuck in open position. Oil?
10	25 Mar 87	120	Information pending.

Table F-5 describes the ten largest product spills (71 to 450 bbl, or 2,982 to 18,900 gallons) on the North Slope during the same period. Causes include broken fuel lines, corrosion, faulty valves, and human errors (e.g., accidental overfill). The ten largest crude oil and products spills from TAPS Pump Station 1 to Atigun Pass are listed in Tables F-1 and F-6; most were generally caused by equipment malfunction or operator error (Maxim and Niebo 2001b).

Table F-5 Ten largest products spills on the North Slope 1977-2000 (Modified from Maxim and Niebo 2001b).

Number	Date	Volume (bbl)	Description
1	22 Aug 81	450	Corrosion caused a connection to fail. Material was contained on the pad.
2	31 Oct 82	200	Diesel tank was overfilled, spilling diesel into a secondary containment dike.
3	19 May 97	180	Broken needle valve on the fill line of diesel storage tank. Diesel drained into a lined containment area.
4	19 Jun 83	114	Differential settlement of a temporary holding tank. Released material was released into dike below tank.
5	21 Nov 80	102	Broken fuel line.
6	16 Oct 86	100	Broken fuel line.
7	7 Feb 77	100	Broken fuel line.
8	22 May 85	95	Faulty connection on a diesel tank truck.
9	31 Jul 91	75	Spray from hole in annulus.
10	8 Jun 81	71	Liner cracked due to extreme temperatures. Fluid contained within it seeped into the ground on Challenge Island.

TABLE F-6 Ten largest products spills from TAPS: Pump Station 1 to Atigun Pass 1977-2000 (Modified from Maxim and Niebo 2001b).

Number	Date	Volume (bbl)	Description
1	14 Oct 88	203	Truck overturned at mile point 258 of haul road, spilling diesel fuel.
2	27 Sep 92	190	Tank truck overturned just north of Atigun Pass, spilling turbine fuel.
3	12 Oct 79	95	Gasoline spilled at Ice-cut Hill due to operator error.
4	20 Jun 82	86	Tank valve at Franklin Bluffs camp left partially open, causing diesel fuel leak.
5	12 Sep 77	83	Diesel fuel spill at Pump Station 3, operator error.
6	9 Jan 86	52	Overturned trailer at Atigun pass, diesel fuel spill.
7	19 Dec 90	43	Tanker jack-knifed at mile poing 85, spilling diesel fuel.
8	19 Jun 79	39	Loader caused diesel spill after excavating and rupturing a fuel line near the metering building at Pump Station 1.
9	24 Jun 86	36	Leak in underground gasoline storage tank at Pump Station 1.
10	16 Oct 78	21	Equipment malfunction at Pump Station 4 temporary camp caused a diesel fuel spill.

Source: TAPS Owners 2001

Environmental impact statements contain hypothetical scenarios featuring spills greater than 1,000 bbl (42,000 gallons). Most large spill scenarios involve a "blowout," that is, loss of well control, which can occur due to (1) a failure of a rig's blowout prevention equipment resulting in a surface blowout, or (2) a failure in the well's cemented casing resulting in a subsurface blowout (Mallary 1998). Pipeline failures, accidents, or even vandalism also can result in large spills.

Fairweather (2000) distinguished between and *event* (uncontrolled flow of liquids or gas from the wellbore, at the surface) and an *incident* (when the pressure on the formation fluids exceeds the pressure of downhole drilling fluids, but does not result in uncontrolled flow at the surface). Table F-7 lists all reported events (5) and incidents (6) on the North Slope between 1977 and 2001. The events resulted in the release of either dry gas or gas condensate resulted in minor environmental effects (Mallary 1998). No oil spills or fires resulted from any of the events or incidents. Over this period 4,965 wells were drilled or redrilled (Alaska Oil and Gas Conservation Commission) so the event/incident frequency is 5/4956 or approximately 1 per thousand wells drilled. This is comparable in order-of-magnitude terms to rates in other areas (Mallary 1998, Ross et al. 1998). The conclusion of these analyses is that blowouts that result in

Table F-7 Loss of well control event and incidents on the North Slope, 1977-2000 (Modified from Maxim and Niebo 2001b).

Number	Type	Well Name	Year	Operator
1	Event	CPF1-23	1979	Arco AK
2	Event	F-20	1986	BP AK
3	Event	J-23	1987	BP AK
4	Event	Cirque #1	1992	Arco AK
5	Event	1-53/Q-20	1994	BP AK
6	Incident	Tunalik Test well #1	1978	USGS
7	Incident	DS 15-21	1980	Arco AK
8	Incident	Challenge Isl. #1	1981	Sohio AK
9	Incident	L5-36	1989	Arco AK
10	Incident	3F-19	1996	Arco AK
11	Incident	1H-15	1996	Arco AK

large spills are unlikely. This finding has been affirmed in several recent environmental impact statements, and may be attributable in part to the strengthening of drilling regulations following the Santa Barbara blowout in 1969 (BLM/MMS 1998, MMS 2001, Parametrix 1997).

The environmental assessment for the Alpine field includes a well blowout as a "reasonable worst case" oil spill (Parametrix 1997). Similar analyses were made for both Northstar and Liberty developments (Ross et al. 1998). The spill contingency plan for the Kuparuk oil field includes a hypothetical loss of well control scenario (Alaska Clean Seas 1999). The plan details include a description of the hypothetical event (location, date, duration, type of spill, weather conditions. quantity of oil spilled) as well as descriptions of how the discharge would be stopped, how to prevent or control fire hazards, a well control plan, methods for tracking oil, spill control, containment, and recovery actions. These contingency plan features are now required by the Alaska Department of Environmental Conservation (ADEC).

Table F-8 lists the five largest North Slope oil spills that have actually contacted tundra soil and damaged tundra vegetation during the period from 1977 to 1999. An additional crude oil/produced water spill occurred in 2001. The area of tundra affected by these spills ranges from 125 to 1,700 m^2 (1,350 to 18,300 ft^2) (McKendrick 2000), with a total area of tundra affected by crude oil and products spills on the North Slope of about 20 acres (8 hectares) (McKendrick 2002).

Table F-8 Five largest crude oil or mixed crude oil/water spills that affected tundra vegetation on the North Slope 1977-1999. (From McKendrick 2000).

Year	Oil Field	Containment Area (m)	Tundra Affected (m)
1989	Kuparuk	5,800	1,700
1994	Kuparuk	930	465
1972	Prudhoe	560	220
1993	Kuparuk	400	200
1985	Prudhoe	350	125

AGRA (2000) developed a tundra spills database as part of a contract for ADEC. It contains information on approximately 200 spills of various sizes. Some general conclusions can be drawn from a review of the data. First, large spills tend to cover between 0.1 and 0.4 ft^2 (0.01 to 0.04 m^2) of tundra per gallon of spilled material. Smaller spills have a greater proportional coverage. Second, area coverage and environmental effects vary with season. Spills during summer generally result in greater effects on tundra vegetation. Some spills result from pinhole leaks in pipelines. These may spray oil over a broad area, but oil tends to remain on surface vegetation. These spills have fewer long-lasting effects than spills in which oil reaches sediments and plant root systems.

Approximately 65-80% of all crude oil and products spills were confined to an individual pad (BLM and MMS 1998). Spills not confined to a pad are usually confined to an area adjacent to the pad or roadbeds off the tundra surface. Spills that occur during winter, on snow, are almost completely removed from frozen tundra by spill response activities (BLM/MMS 1998).

Spill Trends

Time trends in the data can reveal if progress has been made in spill prevention. They also provide a basis on which to forecast future spill volumes. It makes most sense to examine the time trend in the volume of crude and product spilled, rather than the number of spills, because the reporting threshold for spills has decreased over time, and spill reporting has improved. Therefore, any trend in the number of spills is confounded with changes in reporting conditions. For North Slope oil activities the most appropriate exposure variable is the volume of crude or product spilled per unit of production or throughput, the volumetric spill rate, the VSR (Maxim and Niebo 2001b).

Figure F-5 shows annual VSRs for the North Slope from 1977 to 1999. The graph shows that there is a great deal of year-to-year variability in VSRs (solid line). The "bad" years result from a few larger spills, and "good" years from the lack of large spills. The large inter-annual variability makes it difficult to detect trends, especially modest trends, but the data suggest that VSRs have decreased over the years since North Slope production began. The fitted trend (semi-logarithmic) for these data is shown by the dashed line in Figure F-5. The slope of this line is negative, suggesting perhaps some progress in reducing spill rates. However, the percentage variation explained by this regression ($R^2 = 0.117$) is relatively low, and statistical analysis of the regression coefficient indicates that such a trend might have occurred due to chance ($P = 0.07$) (Maxim and Niebo 2001b).

Although the apparent time trend is not statistically significant, numerous modifications made to North Slope facilities and operations practices have been designed to reduce spills. In addition, the accuracy of oil spill data may have increased after 1985 (MMS 2001) or 1989 after the *Exxon Valdez* spill (BLM/MMS 1998) and subsequent legislation and regulations. The reporting threshold for spills has decreased over the years, as well. Therefore, by today's standards, spills were probably under-reported in earlier years (Maxim and Niebo 2001b).

The introduction of improved technologies, engineering designs, or operations practices designed to reduce spills have been both continuous processes and triggered by discrete events. Major ("step") changes in technology or procedures often result from specific events (e.g., a large spill or other accident) and regulatory responses to such events. The key event for both regulatory and industry initiatives was the Exxon Valdez spill in 1989. The Oil Pollution Act of 1990 was implemented along with regulations aimed at both prevention and response. At the same time, oil companies examined and strengthened internal prevention and response programs. Figure F-6 shows VSR data with separate average values (dashed lines) calculated for the time periods prior to and after 1990. The average value for the post-1990 time period is 31% lower than for the years 1977 to 1989.

The VSR for the TAPS segment from Pump Station 1 to Atigun Pass (Figure F-7) does show a statistically significant reduction over time.

Spill Prevention

State and federal regulatory agencies and the oil industry have studied each spill incident, to develop "lessons learned," and measures to reduce the likelihood and effects of future spills. For example, the 575 bbl (24,150 gallons) crude oil spill that occurred on 30 December 1993 (Table F-2) resulted when wind-induced vibration caused a crack in a flowline leading from a well house to the manifold building. Although this failure mode was anticipated and "first generation" wind-induced vibration dampers had been developed, they were not installed on this pipeline. Immediately following the spill, the pipeline was fitted with a vibration damper, along with all other pipelines not already fitted. The design was also improved as a result (Norris et al.

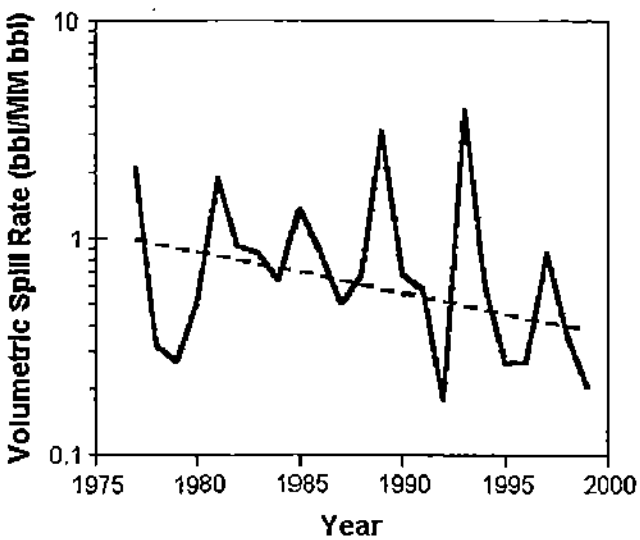


FIGURE F-5. Volumetric spill rates for crude oil and products spills associated with exploration and production activities on the North Slope. Year-to-year variability may mask significance of fit ($p = 0.07$). Source: reprinted with permission from Maxim and Niebo 2001.

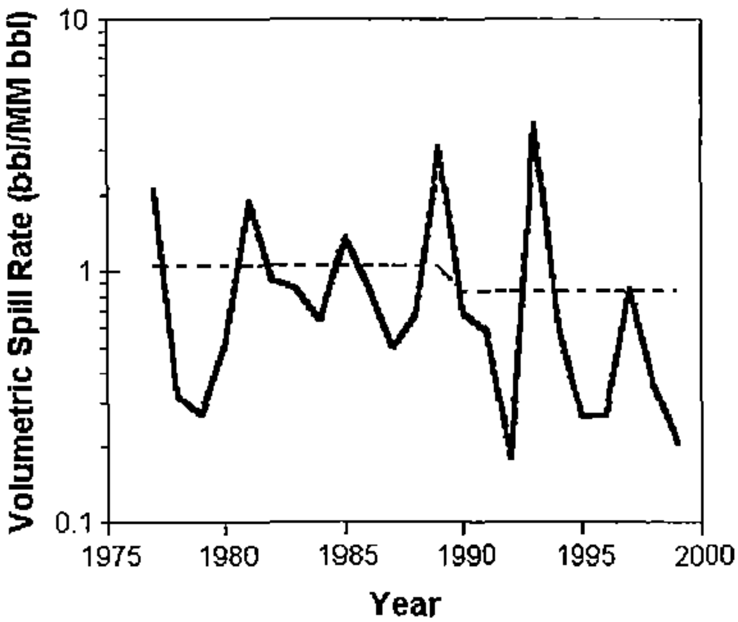


FIGURE F-6. Volumetric spill rates for crude oil and products spills associated with exploration and production activities on the North Slope. Average VSR FRP, 1990-1999 is 31% lower than for 1977-1990. Source: reprinted with permission from Maxim and Niebo 2001b.

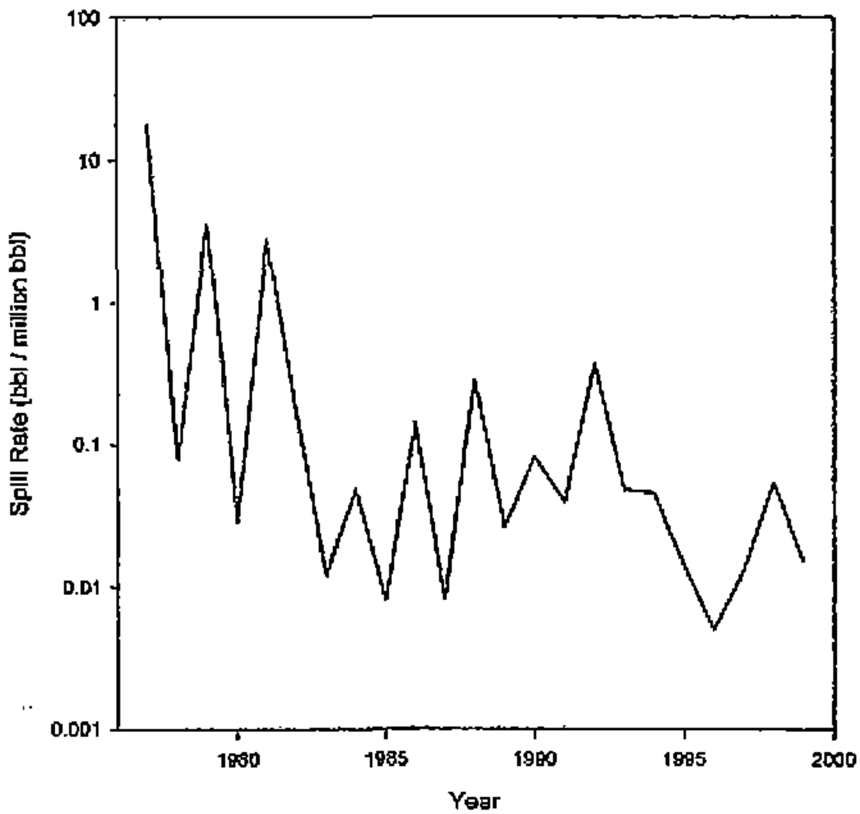


FIGURE F-7. Volumetric spill rate for crude oil and products spills associated with the Trans Alaskan Pipeline from Pumpstation 1 to Atigun Pass (semi-log scale). Source: reprinted with permission from Maxim and Niebo 2001.

2000). Dampers are required only on pipelines less than 24 in. (61 cm) in diameter, oriented perpendicular to prevailing east-west winds and having a specific weld type (Norris et al. 2000).

Prevention of spills can be approached in two ways. The first is changing engineering design and equipment, and the second is changing operating procedures and practices. Table F-9 includes examples of both kinds of changes that have been implemented on the North Slope. The following discussion is descriptive and does not quantitively evaluate the success of those methods.

Table F-9 Spill Prevention on the North Slope (After MMS 2001, Pavlas et al. 2000, Cederquist 2000, Guilders and Cronin, Maxim and Niebo 2001b).

Changes in Engineering Design and Equipment

- Redesign of a component system to reduce probability of leak, e.g., "vertical loops" replace valves in common carrier sales pipeline.
- Use extra thick steel walls, fusion-bonded epoxy coating and cathodic protection to minimize corrosion leaks in pipelines.
- Improve "smart pigs"
- Siemens-developed leak detection and location system
- Use system control and data acquisition system (SCADA) to improve leak detection (similar to TAPS)
- Construct secondary containment around tanks.
- Double-wall storage tanks
- Change pad grading to create a low spot in the center of the pad.
- Development of improved well cellar spill containment system.

Changes in Operating Procedures and Practices

- Location of Major Facilities
  - Avoid environmentally sensitive areas
- Location of storage tanks
  - Avoid river crossings
  - Avoid sensitive wetlands
- Use revised inspection and maintenance procedures (e.g., smart pigs, more frequent inspections)
- Double checking connections before beginning fluid transfer.
- Stepped up monitoring for corrosion.
- Use of corrosion inhibitors
- Use drip pans to collect oil leaks from vehicles.
- More/improved training and classes.

Changes in Engineering Design and Equipment

Changes in engineering design or equipment include new "vertical loop technology to replace block valves, improved leak detection systems, developing and installing double-wall storage tanks and secondary containment structures, alternative design of well cellars, use of "smart" pigs.

The Alpine pipeline uses "vertical loops" in place of block valves (Pavlas et al. 2000, Cederquist 2000). Vertical loops are regular expansion loops of the pipeline with the outboard run lifted to a predetermined elevation. The loops form a terrace structure that, in the event of a leak, limits oil spilled due to drain down effects caused by pipeline elevation differences. Seven 40 to 45 ft (12 to 14 m) high vertical loops were built into the 34 mi (55 km), 12 in. (30 cm) crude oil pipeline. This design was recommended by an oil spill isolation strategy study that systematically evaluated alternatives, including use of conventional block valves throughout. The analysis concluded that, if used with emergency pressure letdown valves or divert valves, vertical loops would contain drain down related spills as well or better than block valves while offering operations and maintenance efficiencies. Use of this technology eliminates the need for remote and manually operated valves that can fail and/or introduce additional leak sources at flanges, valve stems, and fittings. Use of vertical loops is limited to relatively flat terrain, which makes them applicable on flatter areas of the North Slope (Maxim and Niebo 2001b).

Rapid and accurate leak detection can reduce the quantity of crude oil or product spilled. Systems for leak detection include volume balance and mass balance systems (e.g., pressure point analysis). The recently developed Leak Detection Location System (LEOS) for monitoring ethylene pipelines (Comfort et al. 2000; Intec Engineering, Inc. 1999) has been modified for crude oil pipelines. It detects leaks by periodically sampling the vapor within a special, permeable tube strapped to the pipeline. The gas in the tube is sampled by pushing a column of air past a gas "sniffer" at constant speed. The sensor measures vapor concentration and relative distance along the length of the tube, allowing determination of the size and location of the leak.

A well cellar is a cement-lined containment structure surrounding each well. The design was modified to reduce the possibility of subsidence caused by melting permafrost as well as improved containment of leaks and drips from valves or fittings. Each cellar contains a drip pan.

Pigs are mechanical devices that are pushed through a pipeline by flowing crude oil or product. Over the years, pig design has become very sophisticated, leading to various types of "smart" pigs. These pigs are used to monitor the condition of the pipeline, initially establishing a baseline against which future pigging (monitoring) results may be compared. Three types of pigs are used. All can provide early warnings of weaknesses where leaks might occur (Maxim and Niebo 2001b).

- Caliper pig—used to measure internal deformation such as dents or buckling.
- Geometry pig—records configuration of the pipeline system and determines displacement.
- Wall thickness pig—measures thickness of pipeline wall.

North Slope pipelines are insulated to reduce heat loss and reduce the likelihood of corrosion and failure. Weld pack insulation was redesigned, adding a special coating to repel moisture (Maxim and Niebo 2001b).

Containment is one of the generic strategies for spill prevention. Containment prevents further release of spilled material and makes cleanup easier. Measures to maximize containment include double-wall pipes, double-wall tanks, secondary containment structures such as berms and dikes (Pekich, personal communication, 2001, as cited in Maxim and Niebo 2001b).

Changes in Operating Procedures and Practices

Changes in operating procedures and practices include locating storage tanks to avoid environmentally sensitive areas like river crossings, using drip pans to collect leaks, and more frequent inspections. Drip pans are required for all equipment parked on ice pads and roads (including pickup trucks). All stationary tanks greater than 660 gallons have secondary containment (Pekich, personal communication, 2001, as cited in Maxim and Niebo 2001b).

Several spill prevention initiatives are designed to increase spill awareness and reduce human error. These include formal and informal training ("tailgate" or "toolbox" meetings), formation of task forces, appointment of sponsors for various initiatives, and the development and revision of SOPs (Standard Operating Procedures), and checklists (Maxim and Niebo 2001b). Table F-10 is a checklist designed to reduce errors in fluid transfer and transportation operations.

Table F-10 Fluid Transfer Safety Task Assignment (STA) Card Information (Modified from Maxim and Niebo 2001b).

Portable Tank Fluid Transfer Guidelines

Foreman:____________________
Date:____________________
Location/Job:____________________
Truck/Tank #____________________
Driver:____________________
Volume:____________________
Fluid:____________________

All lines closed and secured, capped/plugged?	yes	no	
Portable (or permanent) dikes under truck engine?	yes	no	
Portable dikes under all connections?		yes	no
Camlock seal rings checked?		yes	no
Camlock ears locked and wires closed?		yes	no
Assessment of tank condition before transfer?		yes	no
Bonding cables connected?		yes	no
Fluid level checked before loading?	yes	no	
Vents and hatches in proper position?		yes	no
Sumps and accumulators drained?	yes	no	
Will product foam?		yes	no
Frequent straps during transfer?		yes	no
Tank filled to less than 90% capacity?		yes	no
Inspect location prior to departure?	yes	no	

Comments:

Transportation STA Card Information

Tank Tie-in and Rig Checklist
Date:____________________
Location:____________________
Employee Assigned:____________________
Foreman:____________________

Inspect and report any existing contamination at site	____________________
All hoses and hardline properly connected and diked	____________________
All needle valve bleeds closed and capped	____________________
Inspect tanks (valves closed/capped, demisters, etc.)	____________________
Drip pans beneath all connections	____________________
Orange cones placed along hose/piping connections	____________________
Pressure test all flowback piping	____________________

Spill Response

Response Countermeasures

Research and development on spill response equipment and strategies began after the Santa Barbara spill in 1969. Containment booms, skimming devices, absorbent and adsorbent materials were all developed in the 1970s and have been improved since that time. Since the Oil Pollution Act of 1990 there has been improved design and use of many spill response and logistical support systems. Some of these have been designed or modified with arctic conditions in mind; some may be used anywhere. They include skimmers, fire booms, igniters, air-cushion vessels, airboats, oil/ice processors, oil/water separators, and chemical dispersants. Airborne systems include those that monitor spilled oil, apply dispersants, and ignite oil slicks (Allen 2000). Table F-11 lists major R&D programs for spill prevention and response on the North Slope.

TABLE F-11 Major R&D programs for spill prevention and response (Modified from Maxim and Niebo 2001b).

PREVENTION
1. Corrosion control system (Pekich, personal communication, 2001; Colegrove, personal communication, 2001)
2. Vibration dampers (Carn, personal communication, 2001b; Ford, personal communication, 2001; Henry, personal communication, 2001; Norris et al. 2000)
3. Leak detection and location system (Intec Engineering 1999, Comfort et al. 2000)
4. Expanded vertical loops/antisiphons (Lipscomb, personal communication, 2001; Cederquist 2000; Pavlas et al. 2000)
5. Horizontal directional drilling with remotely located wells (Baker 2000)
RESPONSE
1. Forward looking infrared (FLIR) (Colegrove 2001)
2. Oil recovery from broken ice (Dickens and Buist 2000, D.F. Dickens et al. 2000)
3. In-situ burning (S.L. Ross Environmental Research 1998b)
4. Viscous oil pumping (Majors 2001, S.L. Ross Environmental Research 2001)
5. Oil emulsion breakers (S.L. Ross Environmental Research 2001)
6. Tundra flush programs (Schuyler, personal communication, 2001)
7. LORI stiff brush skimming system (Majors, personal communication, 2001; S.L. Ross/D.F. Dickens 2001)
8. Mutual aid drill (Majors, personal communication, 2001)
9. New trench and weir design (Alaska Clean Seas 1999a)
10. Oil spill response barge for arctic work (McHale 1999)

Much effort has gone into developing these systems, but they are seldom tested or used in training with real oil. Experimental spills have been conducted in other countries, but very few have been permitted in the U.S. since the early 1980s. The effectiveness of that response would likely improve if responders had the opportunity to practice and test equipment on real oil (Allen 2000, Lindstedt-Siva 1995), although broken ice remains a major challenge for response in the Arctic Ocean.

Although all oil spills on the North Slope have been onshore, preparedness is required for both onshore and offshore spills. Alaska Clean Seas, an industry-funded oil cleanup cooperative, is designated as the sole entity responsible for training, purchasing and maintaining equipment, and spill response, including cleanup. Equipment is stored at various locations across the North

Slope. Training and drills are held on a regular basis, including mutual assistance drills, tabletop drills, full-scale spill drills, and safety training.

Onshore Spills

Tundra vegetation can hold large quantities of oil, which prevents oil from spreading over large distances but produces heavy concentrations of oil in the area affected. Standard treatment is low pressure flushing to mobilize the oil and remove it, along with removal of the most heavily contaminated soils. Scraping the surface is designed to leave plant parts (roots, rhizomes) intact so that sprouting will occur the following spring (Cater et al. 1999).

Bioremediation has also been attempted with some success by adding nutrients to the soil and removing snow to increase the growing season (Cater et al. 1999). Most tundra soils contain adequate numbers of hydrocarbon-degrading microorganisms, making in-situ bioremediation possible through addition of nutrients (AGRA 2000).

Most spills during winter on snow have been a light surface aerial spray from a small pin-hole. The pressure and wind blow the oil over a relatively large area, but the coating is light and does not penetrate the snow's surface crust. Vegetation that penetrates through the snow is contaminated. Cleanup is by scraping the snow surface and the affected vegetation, and removing contaminated material. Tundra growth is usually normal the following spring, but there have been minor vegetation effects (Joyce 2001). Cleanup while the ground is still frozen may prevent contaminants from soaking into soil or the tundra mat (AGRA 2000).

Large volume spills on snow melt snow for some distance down drainage. The oil eventually cools and is absorbed by the snow. Cleanup involves making snow berms to contain the oil. Most oil stays on the frozen tundra surface, so scraping the surface is the common cleanup method. The worst-case condition is when some of the oil gets below the frozen surface while it is still warm and can melt the ground and migrate down slope. This kind of spill is cleaned up as if it were a summer condition spill. Down-slope flow is stopped with sheet piling or another barrier. Once contained, contaminated soil and vegetation are removed and remediation takes place in spring. The impacts of such a spill are similar to a spring/summer spill (Joyce 2001).

Burning onshore spills has been tested on tundra, both during winter and the summer growing season. Burning during summer damaged plant communities. Burning during winter had less impact on plants and did not harm permafrost. It may be a viable approach to spill cleanup in winter (McKendrick and Mitchell 1978). Burning was tried recently on a small spill on tundra that the committee observed during a site visit. The spilled oil (from a pin-hole leak in a pipeline) was sprayed over tundra and seemed to contaminate surface vegetation more than soil. Contaminated vegetation was burned.

Spills that flow into running or standing water are contained and removed using booms, skimmers, and sorbent materials (AGRA 2000). Spills on gravel pads are cleaned by removing contaminated gravel according to ADEC standards (ADEC 2001). Contaminated gravel is removed to a central storage location. Periodically this gravel is remediated and reused. Contaminated gravel is rarely left in place but contamination beneath buildings or other structures that prevent immediate removal may remain (van der Wende 2002).

Offshore Spills

Even though there have been no major offshore spills on the North Slope, methods used to control offshore oil spills have been used for 30 years, during which time they have been improved and refined. They are: mechanical containment and recovery, in-situ burning, chemical dispersion. The fate of oil spilled in the ocean is discussed later in this appendix.

Mechanical Control

Mechanical containment and recovery equipment is used to contain oil spilled on water and recover it from the water surface. Containment booms are devices that float on the water surface with an extension (skirt) below the surface. Floating oil contacts the boom that holds it, and may thicken it. Booms are often used in combination with skimmers of various designs that remove oil concentrated within the boom from the water surface. Booms may also be used to deflect spilled oil from a sensitive area. Some booms have been especially adapted for use in ice-infested waters (Abdelnour 2000). The benefit of mechanical recovery is that it removes the oil from the water surface. The disadvantage is that the containment and recovery process is slow, and it usually removes only a small percentage of the spilled oil (Allen 1999).

In most areas of the U.S., mechanical containment and recovery of spilled oil is the first choice of most regulatory agencies. Logistical and efficiency problems increase under the common adverse conditions in the arctic. During freeze-up and break-up unstable ice conditions can significantly reduce chances of reaching and recovering spilled oil safely and effectively (Allen 2000). Much research has been conducted, and design of skimmers, booms, oil/water separators has been improved (Abdelnour et al. 2000, Allen 2000, S.L. Ross Environmental Research 2001a).

In the fall 2000 a series of exercises, using popcorn to simulate oil were held to evaluate the effectiveness of mechanical control and recovery techniques using equipment and methods called for in North Slope contingency plans. Broken ice conditions ranged from 30 to 70 percent ice coverage (Robertson and DeCola 2001). The aim of the exercise was to establish Realistic Maximum Response Operational Limits (RMOL). A barge-based recovery system was tested and RMOL's were determined to be (Robertson and DeCola 2001):

~ 0-1 % in fall ice conditions
~ 10% in spring ice conditions without ice management
~ 30% in spring ice conditions with extensive ice management

These numbers are only estimates, but they strongly suggest that reliance on mechanical recovery to clean up spills on the North Slope is unlikely to be successful.

Since recovery of spilled oil in broken ice conditions remains a major challenge, development of such technology has been an R&D priority (S.L. Ross Environmental Research Ltd. 1998c). North Slope operators established a study team to examine options to deal with oil spills during freeze-up and break-up and define the realistic maximum response operating limitations. The main conclusion of this study team was that "mechanical containment and recovery techniques have limited application for a large spill, especially one from an open-orifice blowout" (D.F. Dickens et al. 2000).

In-situ Burning

If oil is of sufficient thickness and has sufficient volatile components, it can be ignited and burned. On open water, this technique may involve special booms, igniting agents, and methods to deliver them. There has been much research and development on this technique because it is especially applicable in the arctic (Allen 1999). The benefits of burning are that it removes the oil from the environment and it may be more efficient than mechanical recovery, especially in the arctic where a slick may be contained by ice. The disadvantage is that burning oil produces smoke plumes. Another disadvantage is a limited "window of opportunity" when burning is possible. Evaporation of the oil's most volatile components or formation of a water-in-oil emulsion can render a slick not ignitable. S.L. Ross Environmental Research (1998b) studied the "window of opportunity" for in-situ burning of oil on water in the arctic. They found that applying chemical breakers to emulsions contained in fire resistant booms can allow otherwise ignitable slicks burn successfully.

Chemical Dispersion

Dispersants are applied to the surface of an oil slick. They act at the oil-water interface, reducing interfacial tension and breaking the slick into tiny droplets that disperse in the water column (S.R. Ross 2000). Dispersants are most effective if used early, during a fairly narrow window of opportunity. Dispersants are most effective on fresh, low viscosity oils (Ross 2000). The benefits of dispersion are that large slicks can be treated in a short time from the air, and they remove the slick from the surface. Present day dispersants are all less toxic than oil, and applied at lower concentrations than oil. Therefore, dispersant toxicity is less important than toxicity of the dispersed oil (NRC 1994). The disadvantage is that, if effective, dispersion introduces a plume of dispersed oil into subsurface water where it may affect water column and shallow benthic communities. This is usually a very short-term exposure due to the effects of dilution and currents. Dispersents are probably not appropriate for highly viscous oils (Ross 2000). Regulatory agencies generally have not made dispersants a priority for North Slope spills.

Pumping Viscous Oils

Most North Slope crude oils form stable emulsions. Weathered but unemulsified oils may have viscosities as high as 10,000 centistokes (cSt). Emulsions formed from these oils may have viscosities of 100,000 cSt or more. Such high viscosities pose problems for spilled oil recovery activities because pumping these oils is difficult. Solving this problem is another R&D initiative. Several possible techniques might be used to reduce the viscosity of emulsified oils, including heating, use of chemical additives to break the emulsion, and use of chemicals to serve as drag reduction agents. Another technique that has been proposed is annular water injection to reduce line pressures. A relatively small volume of water is injected through a specifically designed flange. The flange causes the water to form a thin layer that coats the inside wall of the hose or pipe, lubricating the flow of fluid and reducing line pressure (Maxim and Niebo 2001b).

Spill Monitoring

Forward Looking Infrared (FLIR) technology was originally developed by the military for reconnaissance and targeting. Since FLIR became available for civilian application it has been adapted for oil spill monitoring. It is carried in an observation aircraft (e.g., DeHaviland Otters) to detect spills along pipelines and pads. It is useful for both prevention and response. It makes possible early detection, and therefore, the ability to minimize the spill volume and extent

(Maxim and Niebo 2001b). It makes it possible to determine the location and extent of a spill, and to distinguish between oil and other substances that may look like oil to the human eye. The airborne FLIR can be used to monitor both onshore and offshore spills.

Research and Development

Restoration/Remediation

The most extensive remediation of a spill on moist-sedge tundra was done following the 2U spill, which occurred in August 1989. This was a spill of 600 bbl (25,200 gallons) of crude oil and produced water that leaked from a valve in the Kuparuk oilfield operated by Arco Alaska. The leak sprayed oil below the pipeline. It pooled and spread downhill, contaminating 1.43 acres (0.60 hectares) of moist and wet tundra, posing several cleanup and remediation challenges (Cater et al. 1999). This was the first relatively large spill on tundra in the Kuparuk oil field, so information was lacking on long term effects of oil spills on tundra, especially the effectiveness and effects of cleanup and remediation methods. The ADEC set stringent standards for remediation, the vegetation in the spill must return to "normal." Normal was to be measured by vascular plant ground cover when compared to adjacent, uncontaminated tundra. The ADEC standard for total petroleum hydrocarbons (TPH) in soil was 500 ppm. After the spill, the most heavily contaminated areas near the pipeline had concentrations of 16,000 ppm TPH (Cater et al. 1999).

During the cleanup, oil sorbents were spread over the area. Low-pressure water flushing with warm and cold water was used to remove oiled sorbent material, along with raking and swabbing. Multiple, short flushes were used to prevent damage to underlying permafrost. Plywood boardwalks were used to prevent trampling. The most severely contaminated soils were removed by scraping off the upper 2 to 5 cm (0.8 to 2 in.), leaving subsurface plant parts (e.g., rhizomes, roots, stem bases) intact. Undisturbed or moderately contaminated areas were not touched. Bioremediation using indigenous microorganisms, adding nutrients, and keeping moisture stable, was also used to reduce oil concentrations in soil. Nutrients and fertilizers were added to enhance indigenous communities of microorganisms. Snow was removed in spring to lengthen the growing season and increase soil temperature. After two summers, the ADEC vegetation requirements were achieved. As of 1996, the hydrocarbon concentrations in the soil were 687 ppm, still exceeding ADEC standards of 500 ppm TPH, although there was a 95 percent reduction from the post-spill concentrations (Cater et al. 1999). Since this was so close to the ADEC standard, the state approved the cleanup (Joyce 2001). Concentrations of oil in soil decreased very rapidly over the first four years, then very slowly after that (Jorgenson, unpublished material, 2001).

As a result of the 2U spill and cleanup, ADEC asked Arco Alaska to do some experiments using surfactants to enhance oil removal from tundra vegetation and soil. Several surfactants were tested, and it was found that small amounts of Dawn® liquid dishwashing detergent mixed with water enhanced oil removal. Multiple, short flushes were used to prevent damage to underlying permafrost. This method greatly enhanced the recovery of spilled oil and had no measurable effect on tundra vegetation (Cater et al. 1999). (Dawn® has also been used to clean oiled birds.)

Seeding has been used to reestablish plant cover in areas where tundra has been damaged by spills. Fertilizer is also applied, with or without seeds. Fertilization accelerated and improved recovery of mosses, grasses, forbs, and shrubs. Seeding may enhance recolonization initially, but natural stocks eventually replace introduced plants (AGRA 2000).

Estimates of Future Spills

Future spill volumes depend on projected values for the VSR and future throughput, neither of which can be forecast with certainty. One projection of future North Slope production is that an additional 7 billion bbl (294 billion gallons) of crude oil will be produced from 2004 to 2034, the anticipated period of the TAPS right-of-way renewal (TAPS Owners 2001). If there is no improvement in the volumetric spill rate (VSR = barrels spilled per million barrels produced), the future value will be equal to the 1977 to 1999 average, approximately 0.86 bbl/million bbl. This amounts to approximately 6,000 bbl (252,000 gallons), an average of approximately 200 bbl (84,000 gallons) per year during the period 2004 to 2034. If the apparent trend is valid, the spill volumes would be lower by 31%. If North Slope production increases, spill volumes will increase accordingly.

An alternate method of forecasting spill volumes is used by MMS (Smith et al. 1982; LaBelle and Anderson, 1985, 1994; Amstutz and Samuels 1984; MMS 1987, 1990ab, 1996, 1999, and 2001a). This method calculates the frequency of large spills (greater than 1,000 bbl) per billion barrels of oil produced. Since no large spills (according to the MMS definition) have occurred on the North Slope, the threshold was reduced to 500 bbl (21,000 gallons) for spill projections for the Liberty field (MMS 2001a). There have been two crude oil spills greater than 500 bbl (21,000 gallons) during the period from 1977 to 1999. Barrels of oil produced over the period were 12.76 billion (535.92 billion gallons), therefore the spill rate is 0.16 spills/billion barrels. MMS (2001a) estimated that there would be 2.74 large spills during the period from 2004 to 2034. These are conservative estimates because they make no allowance for improvement (Maxim and Niebo 2001b).

FATE OF OIL LIKELY TO BE SPILLED ON THE NORTH SLOPE

When oil is spilled into the environment, the fate and effects are determined by the amount and type of oil spilled, the time of year, the environment into which it is spilled, and to some extent, the control and cleanup/restoration methods used. Oil composition and physical characteristics govern its movement, weathering process, and the impacts it has on affected environments. When oil is spilled, it begins to naturally degrade, both physically and chemically. This process is known as weathering and includes spreading, evaporation, dispersion, emulsification, microbial degradation, photo-oxidation. The weathering process is also affected by winds, waves, and currents (BLM/MMS 1998, MMS 2001, USACE 1999).

BEHAVIOR OF OIL IN THE BEAUFORT SEA

Oil spilled during the summer season of open water will spread and weather like other spills in cold waters, influenced primarily by winds and currents. During freeze-up, winter, and break-up, oil will interact with ice and its fate and behavior will be modified accordingly (Dickens and Associates 2000).

Freeze-up

Oil/ice interactions during freeze-up vary with the stage of ice development and ice form (frazil, grease, slush, pancakes, nilas, etc.) as well as the properties of the spilled oil (density, viscosity). All varieties of ice may exist simultaneously, and may change from one form to another rapidly. The progression from less to more mature ice types may be fairly linear at nearshore sites like Endicott and West dock but can be non-linear at locations like Northstar. At nearshore sites, freeze-up progresses from frazil and grease ice to stable new ice in less than a week. Farther offshore, this process may take three weeks or more (Dickens and Associates 2000).

The main factors influencing the degree of oil incorporation into porous developing ice forms (slush, grease, frazil) are oil density and turbulence in the upper water column. The breakdown of oil into suspended particles is also controlled by oil viscosity. Heavier Bunker products are more likely to be break into larger particles, and are less likely to rise to the surface. Most of the oils found in the study area are of lower density and therefore will surface due to buoyant forces (i.e., the density difference between oil and the ice/water mixture). In most situations in the nearshore Beaufort, the turbulent mixing energy in the developing ice field is low compared to open water. Oil droplets or particles of fresh North Slope crude oils will be small enough to rise freely through developing ice (Dickens and Associates 2000).

There have been opportunities to observe oil in developing and broken ice during spills of opportunity and field experiments. Dickens and Associates (2000) describe several of these that, in their opinion, are most applicable to Beaufort Sea conditions. Their general observations and conclusions follow (Dickens and Associates 2000):

1. Landfast ice, when present, provided a protective barrier preventing shoreline contamination.
2. Oil released from under the ice surfaced in leads as they opened.
3. Rough ice such as rubble and rafting ice led to thick oil pools and limited spreading.
4. Crude oil migrated to the surface of slush ice.
5. Barriers of snow and slush in a refreezing lead prevented further oil spreading.
6. Oil continued to evaporate after being mixed or covered by snow.
7. Wind herding created thicker oil layers at the downwind edge of leads.
8. Oil mixed with slush ice and stopped spreading.
9. Most of the spilled oil remained at or near the surface.
10. There is no redistribution of substantial amounts of oil from water onto the surface of ice pancakes or small floes.
11. Oil falling on new or young broken ice under freezing conditions will remain on the ice surface, effectively sorbed by the briny, damp, developing ice and/or snow. In spring,

however, a portion of the oil spilled onto melting ice floes may run off the surface into surrounding water.

12. Most oil spilled subsurface into a developing ice field will be held in concentrated pockets on the underside of the ice. Trapped oil will move with the ice except where there are localized openings in the ice cover or leads where oil can spread on the water surface in the absence of slush. These conditions are short-lived at freeze-up. Open water is unlikely to persist for long at low temperatures.

In the absence of wave action, evaporation is the only significant weathering process that will affect a spill during freeze-up. Evaporation occurs more slowly in the arctic than in temperate climates. However, in a few days to a week, surface oil will lose about the same volume as it would in warmer situations. The result is an increase in density, viscosity, pour point, and fire point of the spilled oil. If pour point exceeds the ambient temperature, the oil will gel. The most likely form of spilled oil remaining after freeze-up is a relatively thick, snow-filled, weathered slick at the ice surface, covered by snow (Dickens and Associates 2000).

Winter

If oil is spilled under stable, land-fast ice in winter, initial spreading will probably be limited to hundreds of meters from the spill source, based on currents and ice storage capacity (Dickens and Associates 2000). Cox and Schultz (1980) found that minimum currents that would move crude oil under a smooth ice sheet were approximately 0.15 m per second (0.50 ft per second), increasing to approximately 0.21 m per second (0.70 ft per second) under the slightly rougher ice representative of midwinter conditions. Under-ice currents in the Beaufort are typically very low (Dickens and Associates 2000).

Another typical phenomenon is encapsulation of spilled oil beneath growing ice that may occur when new ice forms beneath oil trapped under ice. Encapsulation by new ice immobilized the spill quickly, typically within 12 to 72 hours, depending on the time of year. A number of studies have observed this in every month of the ice-growth period from October to May (Dickins and Buist 1981, Norcor 1975).

Oil spilled under ice from a chronic leak may not become encapsulated in the manner described as long as there is a continued source of fresh oil. Although there are no direct observations, it seems likely that frazil present in the water beneath the ice will continue to form and float up into the oil pool as it deepens. At the same time, surrounding unoiled ice will continue to grow and contain the oil from spreading beyond the initial area of oiling. Calculations based on typical ice growth rates show that leaks on the order of 60 bbl (2,500 gallons) per day will be contained in an area approximately 91 m (300 ft) in diameter via this mechanism. The slush/oil mixture will remain a viscous fluid, gradually deepening over time as the cumulative volume increases (BP Exploration 1998).

Normal variations in first-year ice thickness provide natural "reservoirs" that may confine spilled oil to a smaller area compared with an identical volume of oil spilled on open water (Dickens and Associates 2000).

Oil spilled on the ice surface in winter does not spread rapidly due to the presence of snow and natural small-scale ice roughness features. Very little oil is likely to remain under or in the ice at this time.

Vertical migration of oil starts when the expulsion of brine from the warming ice opens pathways to the surface (Dickens and Buist 1981, Norcor 1975). Beginning as early as April, and accelerating through May and June, oil will rise to the surface from wherever it is trapped within or beneath the ice. The rate of oil migration increases once daily air temperatures consistently remain above freezing (Dickens and Associates 2000). The rate of oil migration through an ice sheet is affected by the depth of the oil lens trapped within the sheet (small, isolated oil particles take longer to surface) and the viscosity of the oil (heavier or emulsified oils take longer to rise though brine channels) (Buist et al. 1983, Dickens and Buist 1981, Norcor 1975).

Oil weathering in winter depends primarily on whether or not the spilled oil is exposed to atmosphere. Oil spilled under an ice sheet will not evaporate, but oil spilled on top of ice or into leads does (Dickens and Buist 1981, Nelson and Allen 1982, Norcor 1975).

Oil spilled under ice in winter will be encapsulated into the downward-growing ice sheet. As this process occurs, some oil components may dissolve into underlying water. As is typical, this amounts to only about one percent of the total oil (D.F. Dickens et al. 2000). No further weathering of encapsulated oil occurs until it is exposed to the atmosphere when it appears on the ice surface the following spring.

The formation of water-in-oil emulsion is unlikely with oil spilled under ice since the mixing energy needed to form an emulsion is not present. For the same reason, natural dispersion is expected to be negligible as well (D.F. Dickens et al. 2000).

Break-Up

First ice breakup and the appearance of open water takes place in late May and early June, extending to final breakup in July. The rapid disappearance of nearshore ice in early June is triggered by river overflood (D.F. Dickens et al. 2000). Ice concentrations are highly variable and changeable.

If oil is spilled under ice, it will surface on floes or in leads as ice melts. As the rotting floes fracture and break into progressively smaller ice features, any oil on the surface or in the porous structure of the ice, will gradually enter the water and create localized sheens and patches. Throughout break-up, both residual oil trapped in porous ice and oil on the surface of melting floes will gradually be released to water as sheens and broken thin films. Some oiled floes can strand on shorelines or along barrier islands. The ice will most likely melt in place and release oil into beach sediments (D.F. Dickens et al. 2000).

There is an important difference between oil among broken ice during break-up and freeze-up. There is no slush in the water at break-up. This plus extended daylight, warming temperatures, and decreasing ice concentrations and thickness all combine to make spill response more likely to be effective during break-up (D.F. Dickens et al. 2000).

Once the encapsulated oil is exposed to the atmosphere, it will begin to weather. Evaporation of light components is the dominant process until the ice sheet breaks up, at this time wave action can cause emulsification and natural dispersion of slicks on water (D.F. Dickens et al. 2000).

Oil in meltpools is herded by wind against the edges of the pools. Such slicks may reach approximately 10 mm (0.40 in.) in thickness. Thicker oil will evaporate more slowly than thin slicks and films, but will eventually achieve approximately the same degree of evaporation as slicks on open water. Emulsification of oil in meltpools is not expected to be significant since most are too small to allow generation of wind waves of sufficient size. Rainfall may cause some emulsification but it is likely to be temporary and unstable (D.F. Dickens et al. 2000).

When an ice sheet deteriorates and breaks into floes, oil remaining in meltpools will be discharged onto water between floes primarily in the form of thin sheens trailing from drifting, rotting ice. Once exposed to significant wave action, fluid oil will begin to emulsify and naturally disperse. Weathering occurs more rapidly as temperatures increase (D.F. Dickens et al. 2000).

The implications of these findings for responses to spills are from D.F. Dickens and colleagues (2000).

- Fresh crude oil from both surface and subsurface spills will reside naturally at or near the surface in newly forming ice (grease, nilas).
- Ice acts as natural containment, restricting further spreading from the point where oil contacts the ice surface. However, the presence of ice does not necessarily result in thick films or act to thicken oil once it has spilled.
- All aspects of spill behavior, including spreading and weathering, are greatly affected by the presence of ice. In many cases, the overall effect is to slow or prevent normal weathering and to limit the area of contamination.
- Snow covering oil on ice slows, but does not stop, evaporation.
- Emulsification and dispersion are reduced to almost zero in the presence of any substantial ice cover.
- Attempts at mechanical recovery operations during freeze-up will result in fracturing of the ice and mixing of oil and ice. This would reduce opportunities to recover or burn oil after ice has stabilized.
- Slush or grease ice at freeze-up effectively stops oil from spreading.
- Lack of slush between floes at break-up means the oil is more accessible for recovery and/or burning.
- If the pour point of spilled oil exceeds the ambient temperature, oil on the ice surface will gel. The likely form of most spilled oil remaining after freeze-up is a relatively thick, snow-filled, weathered slick at the ice surface, covered by snow.
- Oil that is spilled under solid, growing ice from freeze-up until April is quickly encapsulated by a new ice layer which grows beneath the oil.
- Oil trapped in ice does not weather (frozen emulsions do not break).
- Oil encapsulated within an ice sheet from a winter spill will naturally rise to the surface beginning in May (exceptions are viscous crudes and emulsions).
- Oil remaining on the ice surface at the downwind edges of meltpools in June and July will be naturally concentrated by wind herding. This facilitates in-situ burning.

Summer

In summer when there is open water, more response options exist. Depending on wind and wave conditions, booming and skimming operations may be effective. In-situ burning using fire booms to concentrate oil is also an option. In some cases, application of chemical dispersants may also be effective, although this does not seem to be a primary strategy on the North Slope.

Offshore

Oil spilled on water spreads due to its relatively low density, and forms an oil slick. The spreading rate and thickness of a slick is influenced by currents, wave action, and the temperature of the water (S.L. Ross Environmental Research 2001a, USACE 1999). Temperature has an important effect on spreading and weathering. At low temperatures, oil is thick and viscous and does not spread as readily as oil spilled in more temperate waters. Viscosity increases as oil weathers, and this can influence the rate of dispersion and emulsification as well (MMS 2001a, USACE 1999).

Evaporation weathers oil by preferentially degrading the lighter hydrocarbons, reducing the overall volume of the spilled oil and increasing its viscosity. Evaporation varies linearly with temperature, faster in warm temperatures, slower in cold temperatures (BLM/MMS 1998). Oil slicks in broken ice or on ice evaporate slowly, while oil encapsulated in ice does not evaporate until it is released during the melting process (BLM/MMS 1998, USACE 1999). Freshwater ice and multiyear ice may not melt during spring thaw and could keep oil from evaporating for years. (The benefit is that the oil is contained and the opportunity exists for a removal project.) For Prudhoe Bay oil, it is estimated that 20% of the oil would evaporate within 30 days following a summer spill or a spring thaw of ice containing a winter spill (BLM/MMS 1998). Similarly, 25-30% of Northstar crude oil released to surface waters would evaporate within the first 30 days based on average temperatures (USACE 1999). The Liberty EIS (MMS 2001a) conservatively estimates that 13-16% of this oil spilled to open water or broken ice will have evaporated. Liberty oil contains more wax and is more viscous than other oils produce on the North Slope (MMS 2001a). Evaporation decreases the toxicity of spilled crude oil as the lighter, more toxic hydrocarbons dissipate. The remaining heavier components may persist in soils and sediments. Even though they are less toxic they may cause chronic, sublethal effects in some instances.

Dispersion and dissolution occurs when oil and water are mixed either by waves, wind, or currents and oil becomes mixed into the water column. Dispersion may also occur when grinding occurs in broken ice conditions forcing water, oil, and ice to mix (MMS 2001a).

Emulsification occurs when water and ice are mixed to form a mousse. This creates two problems regarding spill cleanup. First, emulsification increases the volume of fluid that must be handled, and second, the viscosity of the resulting emulsion can be as much as 1,000 times that of the parent oil, challenging conventional removal and pumping techniques (S.L. Ross Environmental Research 2001b). Emulsification is greatly enhanced in broken ice conditions where grinding ice may form mousse an order of magnitude more rapidly than in open water (BLM/MMS 1998, MMS 2001a).

Microbial degradation may account for a substantial portion of spilled oil removal from marine sediments and shorelines (USACE 1999). Although microbial degradation played a significant role during the Exxon Valdez spill, it is uncertain if it will be as significant in colder North Slope environments. Lower temperatures, limited populations of hydrocarbon utilizing micro-organisms, lack of available nutrients and poor water circulation on the North Slope may hinder microbial degradation of spilled oil (USACE 1999).

Sedimentation and photo-oxidation are other, less significant ways that oil can naturally degrade. Sedimentation occurs when oil particles adsorb to suspended particulate matter and sink to the sea floor. This process can trap oil in seafloor sediments where it may persist (USACE 1999).

Based on their specific gravities and viscosities, none of the crude oils produced on the North Slope will sink naturally, but will remain at the surface when spilled (S.L. Ross Environmental Research 2001). Sinking could occur if oil adsorbs to sediment particles. This has happened in the nearshore waters where there is a high sediment load and mixing energy. It can also result from cleanup activities that mobilize oil that then flows into the nearshore area.

Onshore

Oil spills on tundra are not expected to spread over large areas. The relatively flat coastal summer tundra has a dead-storage capacity of 1.3 to 5.8 cm (0.5 to 2.3 in.), which would retain 74,000 to 370,000 bbl (3.1 million to 15.5 million gallons) of oil per km^2 (BLM/MMS 1998). When oil is spilled on snow-covered tundra, oil spreading is limited because snow acts as a natural barrier. However, if a pressurized pipeline ruptures and oil sprays into the air, it can become widely dispersed on tundra or snow. The nearly constant wind on the North Slope may carry the sprayed oil downwind, depositing it over a large area. BLM/MMS (1998) reported that a spill of 1 to 4 bbl (42 to 168 gallons) of crude oil sprayed mist oil over 100 to 150 acres (40 to 60 hectares).

To better understand the effects of crude oil spills in the arctic, a small amount of oil was intentionally released in a small pond on the North Slope in the summer of 1970. The spill was intended to simulate and average sized spill to a water body during summer. The pond was monitored for nearly a decade. The spill began spreading and evaporating almost immediately. After 24 hours the oil slick had thickened and was pushed by wind to the down-wind side of the pond. Over time the oil spread into vegetation on the down-wind side of the pond and at the end of the first summer was confined to the pond-bottom and vegetation surrounding the down-wind margins. An estimated 50% of the oil evaporated or degraded within a year. During subsequent years, some pond-margin plants were unable to sprout through the oil film there and subsequently died. Additionally, there were measurable, long-term (several year) effects to zooplankton, phytoplankton, and insect population plus shorter-term effects on benthic algae and microbe populations (BLM/MMS 1998).

SCENARIOS OF OIL SPILLS

Beaufort Spill Scenarios

Oilfield operators are required to prepare spill scenarios. Each scenario describes spill location, volume, cause, type of oil, sea, wind, and ice conditions, weather, and spill trajectory. Countermeasures are detailed as well. Scenarios range from small spills to the "realistic maximum oil discharge." The scenarios reviewed were in Oil Discharge Prevention and Contingency Plans required the by Alaska state government.

Pipeline Leak

This scenario is a catastrophic subsea pipeline failure during freeze-up. Spill volume is 2,150 bbl (90,300 gallons). Landfall of the spill on barrier islands is predicted, along with possible impacts on culturally important sites. Shoreline cleanup will be necessary. Some oil will be entrapped in ice. Both mechanical recovery and in-situ burning are recommended spill control measures.

Well Blowout

This scenario is a well blowout during summer, resulting in a 15,000 bbl (630,000 gallons) spill, 1,000 bbl (42,000 gallons) per day over 15 days. Most of the oil (12,800 bbl [540,000 gallons]) spills on tundra. Tundra ponds are also contaminated. Tundra cleanup and rehabilitation are implemented, along with oil recovery from ponds using booms and sorbent materials. Effects on birds are expected, and a bird rescue and rehabilitation program is implemented. The ocean is also contaminated and spill control measures are implemented there. Shoreline cleanup will probably also be necessary.

Chukchi Spill Scenarios

Additional scenarios were prepared for the Chukchi Sea based on assumptions of offshore drill rigs and subsea pipelines (Lewbell and Galloway 1984).

Pipeline Rupture

This scenario is a ruptured subsea pipeline in late summer spilling 5,000 bbl (210,000 gallons) of crude oil in 24 hours. It is assumed the pipeline leak is stopped after that time. There is a 61% chance that landfall of oil will occur between Point Franklin and Point Barrow. Within 30 days, of the oil remaining at sea, 40% would still be on the water surface, 40% dispersed in the water column, 20% evaporated.

Another pipeline rupture scenario, a 500 bbl (2,100 gallons) spill during spring, assumes trapping of some oil under-ice and freezing in place. There is a 61% chance of oil coming ashore within 10 days. Oil trapped in ice could move as far as 480 to 800 km (300 to 500 mi) northwestward.

Well Blowout

This scenario is a June blowout from a wellhead under a drillship, spilling 1,000 bbl (42,000 gallons) per day for 75 days. Landfall of oil is predicted in 33 hours. Under most expected conditions, most of the oil would be transported seaward to the northeast. It could travel 350 km (220 mi) in 75 days.

All of the above scenarios predict oil concentrations in the water column of 1 to 7 ppb (Lewbel and Galloway 1984).

If a spill should occur nearshore, along the Barrow Arch, during winter, the oil might become incorporated within the new ice forming at the edge of the coastal polynya, advected within the polynya, or incorporated into ridges when the polynya closes. Depending on which way the ice is moving at the time, the oil could either be moved offshore with the ice (most likely) or onshore to be released at breakup. The exposure of various portions of the Barrow Arch coastline to spilled oil depends on the site of the spill and the weather at the time. Open coastal areas are more likely to be contaminated by spills than areas protected by barrier islands. Seaward sides of barrier islands are as vulnerable as open coasts. Most lagoons behind barrier islands are protected from oil contamination by these islands. Some lagoons are more vulnerable (Lewbel and Galloway 1984).

North Slope Oil Spill Events Timeline
1977 - 1984
(Modified from Maxim and Niebo 2001b)

	1977 to 1979	*1980 to 1984*
General Events	1968 -Prudhoe Bay discovery announced. 1974 - Prudhoe Bay to Yukon River road construction completed. 1975 - First pipe laid at Tonsina River. 1976 to 1979 – the Petroleum Reserve explored by USGS 1977 - Pipeline completed. 1977 – Oil production at Prudhoe Bay begins. 1977 - 1.800 bbl spill at TAPS check valve 7 1977 - 30 bbl crude oil spill at TAPS Pump Station 1 1977 - One 100 bbl products spill, North Slope 1977 - 83 bbl diesel fuel spill at Pump Station 3 1978 - 21 bbl diesel fuel spill at Pump Station 4 1979 - 1,500 bbl crude oil spill at Atigun Pass 1979 - 95 bbl gasoline spill at Ice-cut Hill 1979 - 39 bbl diesel fuel spill at Pump Station 1	1980 to 1985 – US Fish & Wildlife conducts biodiversity assay in the Arctic National Wildlife Refuge. 1980 -- One 102 bbl product spill, North Slope 1980 - 6 bbl crude oil spill at TAPS Pump Station 2 1981 – Oil production begins at Lisburne Oil Field. Oil discovered- 1967. 1981 – Oil production begins at the Kuparuk Oil Field. Oil discovered -1969. 1981 - 1,500 bbl crude oil spill at TAPS check valve 23 1981 - 5 bbl crude oil spill at TAPS Pump Station 1 1981 -- 71 bbl product spill, North Slope 1982 -- 200 bbl product spill, North Slope 1982 - 86 bbl diesel fuel spill at Franklin Bluffs camp 1983 to 1984 – US Department of energy develops new studies to assess impacts of Arctic Energy development (R&D program). 1984 – August 22, 1984. Largest NS product spill (450 bbl). 1984 - 11 bbl crude oil spill at TAPS Pump Station 3 1984 - 5 bbl crude oil spill at TAPS Pump station 4
Technological Advances	1979 – Alaska Beaufort Sea Response body (ABSRB) is formed as the pre-cursor to Alaska Clean Seas to operate as ANS spill response equipment co-op. 1979? – 'Smart Pigs' are developed as a spill prevention tool.	1983 – Oil companies hold six oil spill cleanup training exercises/ demonstrations. 1983 – ABSRB changes name to Alaska Clean Seas.

Regulatory Events	1969 - TAPS files for pipeline right-of-way permits. 1970 - lawsuits filed to stop pipeline construction. 1973 - Trans Alaska Pipeline Authorization Act becomes law. 1974 - State right-of-way lease issued. 1979 – As a spill prevention policy, the State of Alaska limits seasonal exploratory drilling operations to winter months when the Beaufort Sea is covered by sea ice.	1982 – Original 1979 seasonal drilling laws are revised into two tiers to facilitate exploratory drilling. 1984 – State of Alaska finds: *(1) In situ* burning is the most important component of spill response in broken ice. (2) Volume of oil expected to be recovered by mechanical means is secondary to *in situ* burning. (3) Igniting surface well blowouts can remove the majority of the oil at the wellhead. (4) Seasonal restrictions impact Alaska State economy. (5) Lessees participate in 5-year oil spill research and development program. (6) Increased training for drilling personnel is required. (7) Lessees must be capable of *in situ* burning operations. (8) Drilling is restricted past barrier islands during bowhead whale migration.

Continued -

North Slope Oil Spill Events Timeline
1985 - 1994

Years	*1985 to 1989*	*1990 to 1994*
General Events	1984 -- One 125 bbl crude oil spill, North Slope 1985 – Oil production begins at Milne Point. Oil was discovered there in 1969. 1986 -- One 175 bbl crude oil spill, North Slope 1986 - 52 bbl diesel fuel spill at Atigun Pass 1986 - 36 bbl gasoline spill, underground storage tank at PumpStation 1 1987 – Oil production begins at Endicott oil field. 1987 -- One 120 crude oil spill, North Slope 1987 – Scientific investigation of petroleum development in the Arctic Refuge is done with regard to impact on specific species. 1988 - 203 bbl diesel fuel spill, mile pt. 258 of haul road 1989 – Exxon Valdez spill. 1989 – July 28. 925 bbl crude oil spill at Milne Point Central Processing Flowstation. Largest NS crude oil spill. 1989 – Mixed oil and water spill from production flowline at 2U impacts tundra. Clean-up and remediation. 1989 - 5 bbl crude oil spill at TAPS Pump Station 2 1989 – Industry conducts first mutual assistance drill.	1990 -- One 75 bbl products spill, North Slope 1990 - 43 bbl diesel fuel spill at mile pt. 85, near Pump Station 3 1991 – Oil is discovered at the Badami oil field. 1992 - 190 bbl turbine fuel spill just N of Atigun Pass 1993 – Oil production begins at Point McIntyre. Oil was discovered there in 1988. 1993 -- Four crude oil spills totaling 1470 bbls, North Slope. 1994 – Oil production begins at Niakuk oil field. Oil was discovered there in 1985. 1994 - 18 bbl crude oil spill at Pump Station 1

Years	*1985 to 1989*	*1990 to 1994*
Technological Advances	1985 to 1989 – Alaska Clean Seas focuses on oil in ice spill response. 1989 – Detergent flushing schemes are used on the North Slope to enhance spilled oil recovery. 1989 – First use of wind-induced vibration dampers for spill prevention.	1990 to 1993 – Industry upgrades spill response capability in the state. State focuses attention on shipping in Prince William Sound. 1993 – Wind-induced vibration dampers are installed on some short intra-pad flowlines for leak prevention. 1990 – Alaska Clean Seas charged with slope-wide spill response training and equipment maintenance and inventory. 1994 – Mixed oil and water spill from 1Y1R Flowline. Clean-up response incorporates lessons learned. 199? – Aggressive corrosion control programs are developed. 19?? – Pipeline weld insulation designs are improved. 19?? – Drip pans are used to prevent small spills.
Regulatory Events		1990 – State of Alaska passes oil spill statutes. 1990 – Oil Pollution Act of 1990 passed. 1991 – State of Alaska re-iterates Tier II drilling restrictions. 1991 – Cessation of exploratory drilling in the Canadian Beaufort. 1993 – ADEC promulgates new regulations based on oil spill statutes: (1) Establish a response planning standard of being able to contain and cleanup the worst case discharge in 72 hours. (2) Primary response option is identified as mechanical containment and recovery. (3) *In situ* burning is a response option only if mechanical C&R is not viable.

Continued -

North Slope Oil Spill Events Timeline

1995 - Present

Years	*1995 to Present*
General Events	1996 – Projects to develop the Alpine field are announced. 1996 – Northstar development begins and issues of response capability in the Arctic offshore during periods of broken ice are re-considered. 1997 – Oil is discovered at Sourdough. 1997 -- One 180 bbl product spill, North Slope 1998 – Northstar oil spill contingency plan submitted. 1998 – Oil is discovered in the Sambucca and Midnight Sun Prudhoe Bay satellite oil fields.
Technological Advances	1997 – Extended vertical loops and antisyphons are used on the in place of check valves. This reduces the potential for leaks. 1999 – LEOS system is installed on Northstar to aid in pipeline leak detection. 199? – Second generation of wind-induced vibration damper is developed. 199? – FLIR first used on Alaska North Slope. 2000 – The use of HDD to lay pipe below the Colville River is nominated for ASCE 2000 Outstanding Civil Engineering Achievement of the year. 2000 – Research and development on spills in broken ice leads to tactics for responders. 2000 – Studies show that historical loss of well control has lead to no oil spills and minor environmental impacts. 2000 – By 2000, approximately 30,000 pipeline segments are fitted with wind-induced vibration dampers as a spill prevention technique. 2001 – Well cellar designs which reduce the potential for spills to the environment are developed.
Regulatory Events	1997 – Joint industry and agency task force is set up to consider North slope oil spill response issues. 1997 – ADEC identifies oil spills in broken ice as a major issue. 1999 – Northstar oil spill plan approved by ADEC. 1999 – Fall testing program conducted as part of North Star, Endicott, and Prudhoe Bay contingency plan conditions of approval.

Appendix G:

Saline Spills

INTRODUCTION

Saline water associated with North Slope oil production comes from water produced with the oil or from seawater used for enhanced oil recovery. The produced water is classified as wastewater and injected into Class I and II wastewater wells. Drilling fluids and cuttings generated by drilling and associated wastes derived from processing facilities are also injected into these wells (Maxim and Niebo 2001a).

Seawater has been used in relatively large volumes since 1984 when the Prudhoe Bay waterflood project began. This is a field-wide enhanced oil recovery system that includes facilities to extract and treat water from the Beaufort Sea and then inject it into injection wells. The injected water maintains pressure within the oil reservoir and flushes oil toward recovery wells (Maxim and Niebo 2001a). When this project began it was estimated to enable the recovery of an additional billion barrels from the Prudhoe Bay oilfields (ARCO Alaska 1984). Seawater is also used other purposes, such as testing pipelines for leaks.

Produced water is considered saline, though salinity is highly variable, depending on the field and the amount of seawater injected into the oil bearing strata (Maxim and Niebo 2001a).

Spills of produced water may occur at the wellhead, along pipelines, and at central processing facilities. They may also come from leaking tanks or, in the past, leaking reserve pits.

Reserve pits have been phased out in recent years, and are being dewatered and restored. A recent progress report on the ADEC reserve pit closure program states that as of mid-January 2002, 184 of 329 reserve pits on the North Slope (56%) have been closed, restored, and approved by ADEC (Peterson 2002a). Judd Peterson, ADEC Reserve Pit Coordinator, stated that plans to rehabilitate remaining reserve pits were due in his office on January 28, 2002. He estimates that completion of remaining pit restorations through closure and ADEC approval will take 6 to 8 years. Mr. Peterson also stated that ADEC requires water sampling adjacent to all remaining reserve pits. According to these data, no substances are being leached from these pits that exceed state water quality standards. Some reserve pits contain diesel-based drilling fluids and produce a visible sheen when muds are disturbed. ADEC requires that these be excavated, dewatered, and backfilled on an accelerated timetable even if the diesel cannot be detected in samples. Accelerated restoration is also required for pits subject to erosion and possible contamination of Beaufort Sea waters. Four such sites are currently being restored and a fifth site is scheduled for restoration in 2003 (Peterson 2002b).

Seawater spills from the enhanced oil recovery process can occur at the seawater extraction plant, the seawater treatment plant, holding tanks, along pipelines, and at seawater injection wells. Less common sources include fire control systems, compressors, pig launchers, and meltwater.

Causes of saline water spills along the pipeline include leaking valves, pump failures, leaking pipes, leaking tanks and drums, transfer hoses, o-ring and seal failures, leaking vehicles, and human error. In the past, leaking reserve pits were also a cause of spills.

SPILL DATA

Maxim and Niebo (2001a) examined water spill data from an unpublished portion of the TAPS oil spill database developed by IT Corporation. This spill database contains information on spills of crude oil, refined petroleum products, water, and other substances from 1977 to 1999. The database covers exploration and production activities on the North Slope and the entire Trans Alaska Pipeline. The crude oil and products spills data were presented in TAPS Owners (2001) environmental report. There was some difficulty distinguishing the saline water spills from fresh water spills.

Maxim and Neibo (2001a) compiled spills listed as water, produced water, seawater, wash water, meltwater, gelled water (seawater mixed with chemical enhancer to thicken it - used in enhanced oil recovery), and chemical mixtures. Any spill record that referred to seawater, produced water, or gelled water was considered to be a saline spill for purposes of the analysis. There was no way to separate out the low salinity from the higher salinity (seawater) spills. Some spills did not contain enough information to identify the material spilled, and these were termed unclassified spills. There were 17 unclassified spills between 1977 and 1985. These were excluded from the analysis. Together, they accounted for 0.9% of the total spill volume. In addition, spill records for that period were less complete, and reporting appeared to be less rigorous than it has been subsequently. Therefore, the detailed analysis covers only the period from 1986 through 1999.

Three spills during this period were water mixed with crude oil. These were considered in the oil spill section, only the water portion was considered in the analysis of saline water spill data.

Over the period 1986-1999, there were 929 seawater spills associated with North Slope exploration and production and the North Slope portion of TAPS. Total amount spilled was 40,849 bbl (1,715,658 gallons). This averages out to 66 spills per year over the period and an annual spill volume of 2,918 bbl (122,556 gallons). (See Table G-1.)

Analyses of the TAPS oil spill data have normalized spills to the amount of oil transported (Maxim and Niebo 2001b). This is appropriate for oil spills in establishing time trends, but may not be the best choice when normalizing saline water spill data. Comparing water spilled to the amount of crude oil produced suggests only how well water is being handled in relation to the amount of oil handled and may mask inefficiencies in the ANS water handling system. A more useful analysis may be comparing the amount of water handled on the North Slope with the amount of water spilled.

Seawater used in the enhanced oil recovery process accounted for the vast majority of water used on the North Slope during the period. Annual data on the amount of produced water and water used for enhanced oil recovery is available from the Alaska Oil and Gas Conservation Commission (AOGCC) (McMains 2001). These data were used to calculate the Volumetric Spill Rate (VSR), measured in bbls of water spilled per million bbls of wastewater handled

Table G-1 Number and volume of saline, freshwater, and unclassified water spills on the North Slope. Modified from Niebo 2001a.

Year	Saline water		Fresh water		Unclassified water	
	no.	vol. (bbl)	no.	vol.	no.	vol.
1986	18	955	8	26,923	16	160
1987	20	177	13	19,758	20	17
1988	52	1,098	15	55	39	45
1989	104	3,336	24	231	41	122
1990	139	772	36	117	24	17
1991	132	9,295	36	227	25	168
1992	80	505	37	227	38	16
1993	73	575	35	52	11	7
1994	63	1,728	44	95	12	3
1995	63	1,057	21	216	14	52
1996	56	652	16	32	8	56
1997	52	18,407	21	60	17	71
1998	41	1,910	39	144	8	16
1999	36	383	26	19	25	58
Totals	**929**	**40,850**	**371**	**48,156**	**298**	**808**

(bbls/million bbls). Table G-2 lists the annual water handled, the annual brine spill volumes, and the calculated VSR. Figure G-1 (3) plots the VSR based on volume of water handled (solid line) as well as the volume of oil transported through TAPS (dotted line). The lines match until 1990 when the volume of water handled increased while the amount of oil transported began to decrease.

Table G-2 ANS E&P Saline Water Spill rates (1986-1999). Modified from Maxim and Niebo 2001a.

Year	Spill Volume (bbls)	Volume of Water Handled (bbls)	Annual Spill Rate (bbls spilled/ million bbls handled)
1986	955	588,243,485	1.623
1987	177	689,765,315	0.257
1988	1,098	726,675,694	1.511
1989	3,336	801,407,354	4.163
1990	772	845,450,781	0.914
1991	9,295	894,098,366	10.395
1992	505	983,579,753	0.514
1993	575	1,038,007,615	0.554
1994	1,728	997,105,134	1.733
1995	1,057	1,001,078,993	1.055
1996	652	1,000,648,796	0.651
1997	18,407	1,031,291,327	17.849
1998	1,910	1,004,600,076	1.901
1999	383	671,552,213	0.571
Total	**90,290**	**12,273,505,602**	**3.30**

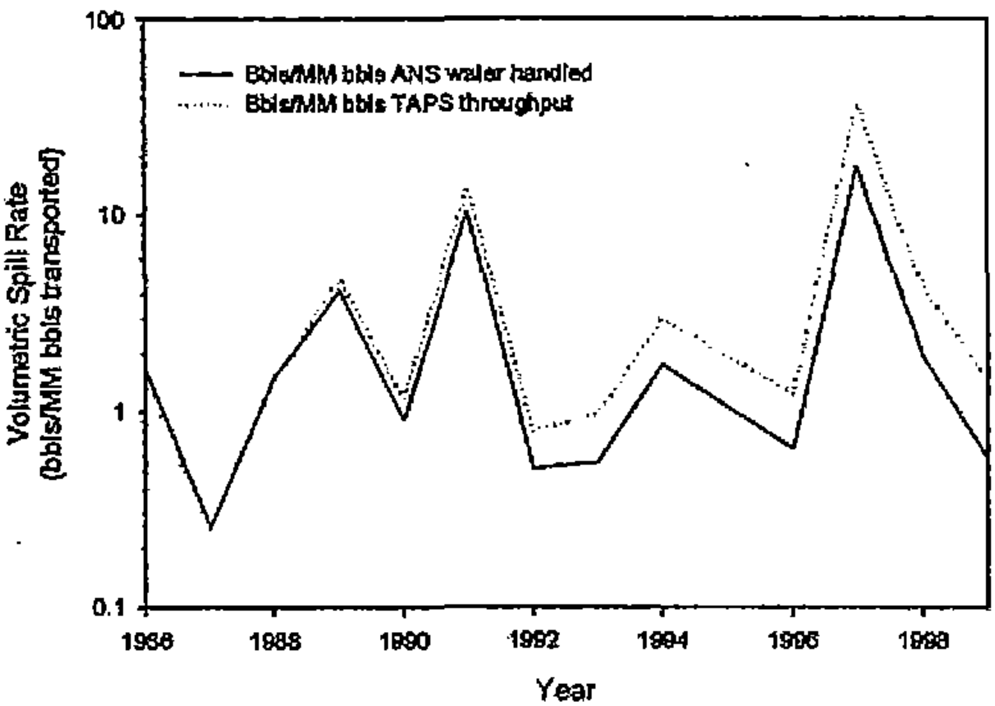


FIGURE G-1. Saline water VSR on the North Slope, 1986-1999. Source: reprinted with authors' permission from Maxim and Niebo 2001a.

Over the period from 1986 through 1999, the average VSR for saline spills based on water handled was 3.3 bbl/million bbl of water handled. If based on the volume of oil transported, the VSR is 5.4 bbl/million bbl transported (Maxim and Niebo 2001b).

As is the case with oil spills, there is substantial annual variability in the VSR for saline water spills—from 0.25 to 17.85 bbl/million bbl. "Bad" years are the result of a relatively few large spills and "good" years result from the lack of large spills, not spill numbers. The years 1997 and 1991 have the highest spill rates (VSRs). In 1997, 18,040 bbl (757,680 gal) of freshwater and diluted seawater came to the surface around several wells. A large spill occurred in 1991 when a valve failed and 8,500 bbl (357,000 gal) of produced water were spilled at Central Processing Facility 2.

The twenty largest saline water spills from North Slope operations during the 1986-1999 period are listed in Table G-3. These range in volume from 210 to 18,040 bbl (8,820 to 757,680 gal). Combined, they account for 85% of the total saline water spill volume.

Table G-3 Twenty largest saline water spills from North Slope operations. Modified from Maxim and Niebo 2001a.

Number	Date	Volume (bbls)	Description
1	17 Mar 97	18,040	Freshwater and diluted seawater surfaced around nine wells at Drillsite 4.
2	01 Jun 91	8,500	Valve failed and leaked produced water at Flowstation 2.
3	16 Dec 89	1,500	Pipeline weld failed, leaking seawater from a seawater injection line along Oliktock road.
4	10 Jan 98	1,500	Pipeline leak spilled produced water.
5	29 Sep 86	500	Fiberglass bypass line on heat exchanger failed, spilling seawater to secondary containment at Seawater Treatment Plant.
6	28 Jul 89	500	Flowstation 2 actuator bonnet failed spilling produced water.
7	31 Oct 94	385	Crack in pipeline 1Y-1R spilled mixture of crude oil and produced water. Only the volume of spilled water is given for this spill.
8	22 Dec 89	355	Pipeline leaked seawater to drill pad. Corrosion suspected.
9	25 Jun 92	350	Water tank overflowed seawater to a sump when valve leaked at CPF-3.
10	07 Mar 94	320	Seawater spilled to drillpad at Prudhoe.
11	14 Apr 94	310	Seawater valve in pig launcher module leaked into pigging pit and overflowed.
12	15 Mar 95	300	Produced water was released to a drill pad and reserve pit when equipment failure caused pressure change in pipeline.
13	07 Nov 95	300	Seawater spilled onto drill pad during equipment malfunction.
14	08 Feb 88	287	Seawater injection line bled water from a pipe rack on a drill pad.
15	30 Mar 88	281	Corrosion caused a produced water leak in a pipeline.
16	17 May 88	250	Solonoid on seawater line at sw treatment plant failed.
17	06 Oct 88	250	Produced water injection line at drillsite failed due to corrosion.
18	01 Nov 96	231	Leak in seawter line at sw injection plant.
19	12 Dec 91	230	Rod failed on seawater pump at central processing plant.
20	07 Jan 96	210	Produced water spilled from pig launcher after an ice plug melted out of a partially open valve.

The volume of reported saline water spills range from 0.0024 bbl (approximately 1.6 cups) to 18,040 bbl (757,680 gal). As with oil spills, small spills are frequent, large spills are rare, and the total volume is dominated by the few large spills. A Lorenz diagram (Figure G-2) provides a useful depiction of these spills. The fraction of spill volume is plotted against the

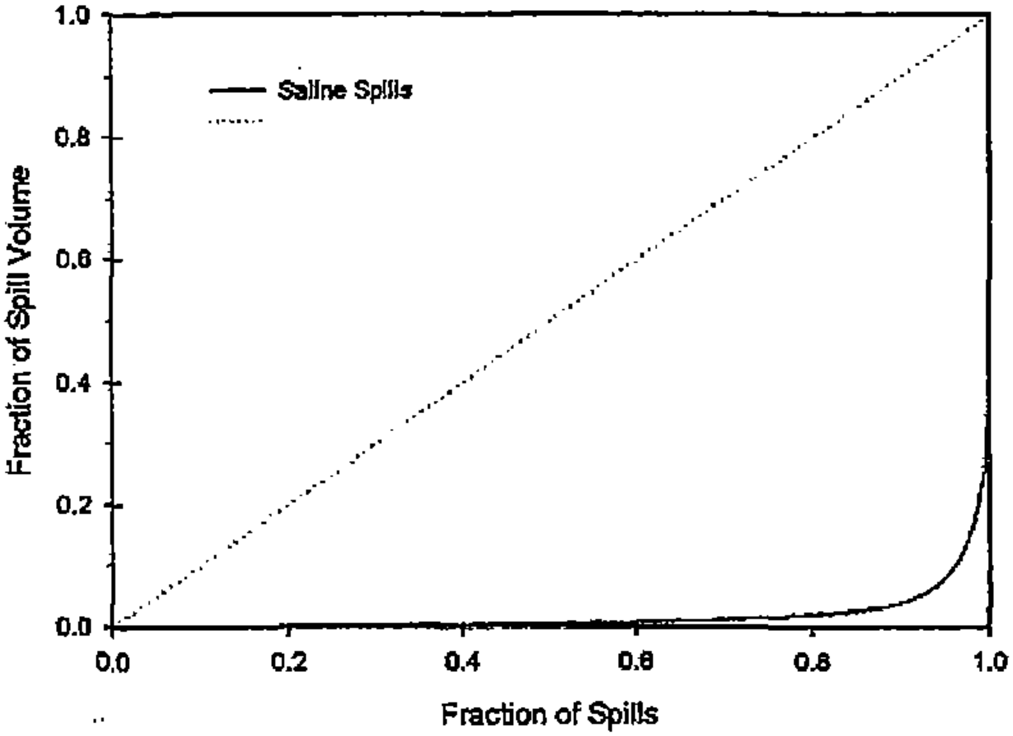


FIGURE G-2. Lorenz diagram of North Slope saline water spills. Source: reprinted with authors' permission from Maxim and Niebo 2001a.

fraction of spills. If all spills were of equal size, the plot would be a straight line. There is substantial curvature in the plot, and the computed Lorenz coefficient is 0.97. It is clear that the relatively few large spills account for the most of the spill volume. In fact, 50% of North Slope saline water spills were less than 0.95 bbls (40 gal), and the smallest 90% of these spills accounted for approximately 3.9% of the total volume, the smallest 95% accounts for approximately 8.2% of the total volume spilled (Maxim and Niebo 2001a).

EFFECTS OF SALINE WATER SPILLS

A study that anticipated potential spills associated with the Prudhoe Bay Waterflood project was sponsored by the Army Corps of Engineering Cold Regions Research and Engineering Lab (CRREL) (Simmons et al. 1984). The purpose was to evaluate the sensitivities of different tundra plant communities to seawater spills. Eight sites representing the range of vegetation types along the pipeline route were treated with single, saturating applications of seawater during the summer of 1980. Each site was examined prior to the experimental spills, monitored closely for 28 days, and visited less frequently over the following year. Symptoms of physiological stress were observed 8 days after the experimental spill. Within 12 days, 17 taxa of vascular plants developed physiological stress attributable to the treatment, ranging from slight chlorosis to total browning and desiccation of all the plants foliage. The impact of seawater treatment was most severe in the mesic and dry sites. The wet sites were less severely affected. Within a month of treatment 30 of 37 taxa of shrubs and forbs in the experimental plots developed definite symptoms of stress, while the 14 graminoid taxa did not exhibit adverse effects. Live vascular plant cover was reduced by 89% and 91 % in the two dry sites and by 54%, 74%, and 83% in the three moist sites. Mosses were unaffected in all but one of the experimental sites. Two species of foliose lichens showed deterioration, while other lichen species were not affected. The absorption and retention of salts by soils is inversely related to soil moisture. In the wet sites, conductivities reached prespill levels in approximately 30 days. Salts were retained in soils at the dry sites, concentrating at or near the seasonal thaw line. Soil enzyme and microfloral activity was reduced for up to one year after treatment (Simmons et al. 1983).

In December 1982 approximately 400 bbl (16,800 gal) of concentrated sodium chloride leaked from a damaged storage tank at a drillsite in the Kuparuk oilfield. The spilled brine spread onto tundra adjacent to the drill pad, covering an area of approximately 0.3 ha (0.7 acre) before freezing (Baker 1985). Soils and vegetation were studied for two years. By the 1983 growing season all plants within 40 to 60 m (130 to 200 ft) of the center of the spill were dead, and up to 30 m (100 ft) beyond the dead vegetation, many plants showed signs of physiological stress. In July 1983, the size of the affected area was approximately 1.6 ha (4 acre). In the fall of 1983 a road was constructed across the western side of the site, altering the local drainage and forming an impoundment in the spring of 1984. By July 1984, the size of the affected area had increased to approximately 4.5 ha (11 acre). Vegetation was dead within 90 to 140 m (300 to 460 ft) of the spill center, and signs of stress were found in plants 40 to 60 m (130 to 200 ft) beyond the dead vegetation (Baker 1985). The study was continued and expanded to map and quantify vegetation types, examine the effects of the spill on thaw depths, document salinity levels in soil and water bodies in the vicinity. Unaffected tundra near the spill zone was used as a reference area.

The area affected by the spill was divided into high- and moderate-impact zones. Forbs and shrubs were most severely affected, graminoids and cryptogams less severely. Some recovery had occurred by 1984, the size of the high-impact zone was decreasing. There was vigorous growth of the sedge species *Eriphorum angustifolium* in the moderate-impact zone (Jorgenson et al. 1987).

In June 2000 approximately 1,200 to 1,500 gallons (28.6 to 35.7 bbls) of low salinity seawater (Electrical Conductivity = 5,020 μmhos/cm; salinity = 3.5 ppt) was leaked from the Alpine oil pipeline during hydrostatic testing. The tundra at this site is moist tussok and wet sedge. The soil active layer was only partially thawed at the time of the spill. The moist tundra was thawed deeper than the wet sedge meadow. The spill site was studied by J.D. McKendrick (2000). As in the previous study, the moist (tussok) community was affected to a greater degree than the wet (sedge) community. Elevated salt levels in surface water bodies were found as far as 58 ft (18 m) from the leak. The area of vegetation damaged by the leak was 6.25 ft^2 (0.1 m^2). In this area salt levels in soil were elevated. Even though plants lost their leaves, they survived and grew normally during the growing season. McKendrick (2000) attributes this to the low salinity of the water spilled. In addition, tundra communities close to the coast may be exposed to seawater during storm surges.

McKendrick (1997) has examined many saline water spill sites, including those treated with fertilizers, or flushed with freshwater or calcium nitrate. He noted much variation in recovery based on such things as grazing pressure. Those sites treated by flushing with freshwater or calcium nitrate recovered faster than non-flushed sites. The calcium nitrate flush was no more effective than freshwater alone. Recovery of flushed sites may still take several years, non-flushed sites may take decades, depending on conditions.

The effects of saline water spills are related to salinity. As expected, low salinity water has less severe initial impacts and more rapid recovery than higher salinity water. Recovery from higher salinity spills may take several years.

Effects of saline water spills can be reduced by flushing with freshwater (Walker 1996). Joyce (2001) reports that the standard response countermeasure in summer is flushing with warm fresh water. In winter, snow berms are constructed to contain the spill and the frozen material is picked up with scrapers.

Appendix H:

Traditional Knowledge

Native American people have since the time of the first European contact struggled with the idea of sharing with the outside world a storehouse of raw information, truisms, philosophies, and ways of life. This storehouse is wrapped in a big blanket and named by the outside world as "traditional knowledge". It has been obtained (as in any culture) over time by observations of nature, trial and error, dogged persistence and flashes of inspiration. In cultures without a written history, such as our Alaskan North Slope Iñupiat culture, this knowledge is passed person to person, through social organizations, individual training, as well as through stories and legends.

Our culture is based on knowledge of the natural environment and its resources. Knowledge of the arctic tundra, rivers and lakes, of the lagoons and oceans, and all of the food resources they provide are our foundation. Further, knowledge of snow and ice conditions, of ocean currents, weather patterns, and their effects on natural systems becomes necessary for navigation, finding and trailing game, and locating shelter and each other. This knowledge has value. First, to pass amongst each other and on to our children, and, second (should we decide to) to pass on to those outside of our culture.

To someone unfamiliar with the Iñupiat culture or the arctic environment (such as a youngster or an outsider) the storehouse of information must seem near infinite and inaccessible. And, stereotypes abound—amongst ourselves and in the eyes of outsiders. Legends of the "hundred different terms for snow… or ice" serve to perpetuate the mystery. Regarding sharing with outsiders, in addition to the stereotypes, there is a stigma: bad experiences too numerous to count that began by good-faith sharing of traditional knowledge and ended by abuses of the sharing process. These range from simple plagiarism to exploitation and thievery. Here, too, legends and stereotypes abound.

Such experiences have led many Iñupiat people first to ask "Why share?" And even if this challenge has been answered sufficiently, an equally difficult challenge remains for both sides: "How to share?"

WHY SHARE?

Why do we share our traditional knowledge? Despite the stigma, our community is proud of a long history of productive cooperative efforts with visiting researchers, and proud of hunters, travelers and other experts lending their support to visiting scientists, map makers and others. Why? We share when we consider others as close enough to be part of our own culture, and we share when we think it is in the best interest of a greater cultural struggle.

Experts Sharing With Each Other

The question of "why" is always easy to answer when two individuals are sharing equally, and the joy of discovery takes place on both sides. Examples in our own hundred-year history of cooperation serve as good models. The wildlife biologist and the whaler, the nomadic traveler and geologist, the archaeologist and the village elders. This two-way exchange has often worked when a given researcher has been around long enough to be considered "one of us," or at least has displayed to the community that he possesses some common values.

Sharing for the Greater Good

For a more locally important reason, we share traditional knowledge when we believe that it will lead to preserving our land, our resources, or our way of life. This reason has prodded us to work hard with regulatory agencies and other organizations to develop policies, to draft environmental impact statements, or to offer even the most specific knowledge of the environment, wildlife, or cultural practice.

Sharing as a Part of Iñupiat Education

A third reason exists: Pure instruction. Like a teacher to a student, our elders and experts teach the rest of our community in any facet of traditional knowledge. We share to perpetuate our culture. How does one become involved in this kind of sharing? The answer is simple: Become a student. However, this can take a lifetime, pairing with a given expert over years of learning. Chances are that the teacher himself is learning, too. This is the method most commonly used by our own people to transfer knowledge amongst ourselves. Our culture has many vehicles to allow this kind of instruction to take place. This method, too, faces challenges due to changing culture, loss of language, and other factors.

HOW TO SHARE?

How can an outsider partake in any of the vehicles of sharing traditional knowledge? Choose one or all above criteria: an exchange among experts, become part of an effort that is of value to our people, or remain in the community and become a real student. Any other method risks lack of context, data gaps from abbreviated efforts, and other such problems.

Current Efforts

Funding exists in many government agencies for programs that elicit traditional knowledge. These programs can be found from NSF to NOAA to MMS. Recently these efforts have drawn praise from outside quarters, as it demonstrates that the government has "validated" traditional knowledge. Yet, even so, we are still struggling with the very agencies that have given traditional knowledge some credibility. Why is this? In many instances the goal of eliciting traditional knowledge is a short-term project objective for an effort that might necessarily take a lifetime.

A common problem many agency efforts face is that they try to gather traditional knowledge in "non-traditional ways." They hold public meetings, offer copies of documents for comment, or rely on whatever political leadership happens to be in place. Another vehicle in vogue for agencies is the contract with a Native organization.

Native tribal organizations, profit and non-profit corporations, and rural and local governments all represent some aspect of a Native constituency. So, because the groups have some legitimacy in attempting to be the bridge between traditional knowledge and the outside world, a contract is developed. The contractor must somehow assimilate, document, and contribute traditional knowledge. Thus, what should take (1) years of heart-to-heart collaboration between experts, or (2) a whole army of local energy focused on a single issue, or (3) years of tutelage under a suite of instructors must now must be completed before the contract deadline, usually a period of weeks to months.

When contracting with a Native organization to elicit traditional knowledge, the government can wash its hands of the issue. It looks appropriate; it's in the Natives' hands. And, the Native organization, hungry as it should be for grants and contracts from the "feds," offers to carry the obligation. Again, contract and project timelines become the targets, and we collect what we can while we can. Quality may suffer, content and context as well.

Knowing that change happens slowly, and that agencies can only do so much, it is reasonable to assume that what is presently occurring will continue. Meetings to assess traditional knowledge will undoubtedly go on. With this in mind, there are a few more cautions to those interested in documenting traditional knowledge, learning about the environment without reinventing the wheel, and working with Native communities on regionally important issues.

Choose the Forum with Care

A meeting's attendees must be matched to the issue. When expertise is really needed, it should be stated. Stereotypes will allow any agency to assume the expertise is there. There is a scene from the movie "On Deadly Ground" where the leading actress (an Oriental woman playing a Yup'ik) jumps on a horse to the surprise of Steven Seagal's character. He asks, "You can ride a horse?" to which she answers, "Of course, I'm Native American!" A comical analogy, but not far from the mark from many real-life stereotypes.

Don't Put Your Eggs in One Basket

Check sources. Stated another way, the most talkative person may not be the most knowledgeable. Ours is a culture of consensus. Agreement is mandatory on nearly every item passed as traditional knowledge. If one person stands alone, he may be an expert, or he may be wrong.

Given the size of the task, it is easy to run away from documenting traditional knowledge, even for our own internal reasons. For many it can be an intensely personal endeavor. Still, such documentation will continue—by our own people as well as by outside groups. Our culture is changing, and some day we may be learning "traditional knowledge" using the same techniques employed by those today who are outside looking in. We may be learning of our own traditional knowledge as if it belonged to others. Just as today in many places we are learning our own language as if it were a foreign language.

As long as we are pledged to the task, we should look past the requirements of this contract or that mandate, and remember the quality of information, time-tested and true. With everything changing, it is a valuable reference plane. If it is not where we are going, at least it is where we are coming from.

Appendix I:

Legal Framework for Activities on State Lands on the North Slope

Source: Final Best Interest Finding, Beaufort Sea Areawide, Appendix B

Laws and Regulations Pertaining to Oil and Gas Exploration, Development, Production, and Transportation

Alaska Statutes and Administrative Code Sections

ADNR

AS 38.05.027	Management of legislatively designated state game refuges and critical habitat areas is the co-responsibility of ADF&G (AS 16.20.050-060) and ADNR. Lessees are required to obtain permits from both ADNR and ADF&G.
AS 38.35.010-260	Right-of-way leasing for pipeline transportation of crude oil and natural gas is under the control of the commissioner of ADNR. The commissioner shall not delegate the authority to execute the leases.
AS 38.05.127	Provides for reservation of easements to ensure free access to navigable or public water.
11 AAC 53.330	Implementing regulations for the reserving of easements to ensure free access to navigable or public water.
11 AAC 83.158(a)	A plan of operations must be approved by the commissioner, ADNR, if (1) state owns all or a part of the surface estate, (2) lease reserves a net profit share to the state, (3) state owns all or part of the mineral estate, but the surface estate is owned by a party other than the state, and the surface owner requests such a plan.
11 AAC 96.010	Operations requiring permits, including the use of explosives and explosive devices, except firearms.
11 AAC 96.140	Land use activities are subject to general stipulations that will minimize surface damage or disturbance of drainage systems, vegetation, or fish and wildlife resources.

ADNR/DO&G

AS 38.05.035(a)(9)(C)	Requires geological and geophysical data to be kept confidential upon request of supplier.
AS 38.05.130	Allows the director, DO&G, to approve oil and gas exploration and development activities in the case where the surface estate is not held by the state or is otherwise subject to third party interests, provided the director determines that adequate compensation has been made to the surface estate holder for any damages which may be caused by lease activities.
AS 38.05.180	Establishes an oil and gas leasing program to provide for orderly exploration and development of petroleum resources belonging to the state of Alaska.

11 AAC 96.010-150	Geophysical Exploration Permit provides controls over activities on state lands in order to minimize adverse activities
ADNR/DL	
AS 38.05.075	Establishes leasing procedures under public auction, including tide and submerged lands, bidding qualifications, and competitive or non-competitive bidding methods.
AS 38.05.850	Authorizes the director to issue permits, rights-of-way or easements on state land for recovery of minerals from adjacent land under valid lease.
11 AAC 80.005-055	Pipeline Right-of-way Leasing Regulations.
11 AAC 93.040-130	Requires a Water Rights Permit for the appropriation of state waters for beneficial uses.
11 AAC 96.010-140	Land use permit activities not permitted by a multiple land use permit or lease operations approval.
ADNR/ DMWM	
11 AAC 93.210-220	Provides for temporary water use permits and procedures for application.
ADNR/DF	
AS 41.17.082	Alaska Forest Resources Practices Act. Requires that all forest clearing operations and silvicultural systems be designed to reduce the likelihood of increased insect infestation and disease infections that threaten forest resources.
11 AAC 95.195	Describes the approved methods of disposal or treatment of downed spruce trees to minimize the spread of bark beetles and reduce the risk of wildfire.
11 AAC 95.220	Requires the lessee to file a detailed plan of operations with the state forester.
ADF&G	
AS 16.05.840	A permit is required from ADF&G prior to obstruction of fish passage.
AS 16.05.870	Provides for the protection of anadromous fish and game in connection with construction or work in the beds of specified water bodies, and calls for approval of plans by the commissioner, ADF&G, for any diversion, obstruction, change, or pollution of these water bodies.
AS 16.20	Management of legislatively designated game refuges and critical habitat areas.
AS 16.20.060	The commissioner, ADF&G, may require submission of plans for the anticipated use, construction work, and proper protection of fish and game. Written approval must be obtained.
AS 16.20.180-210	Requires measures for the continued conservation, protection, restoration, and propagation of endangered fish and wildlife.
5 AAC 95.010-990	Fish and Game Habitat Authority.

18 AAC 50.300	Sets up standards for air quality at certain facilities including oil and gas facilities at the time of construction, operation, or modification.
18 AAC 60.220	Requires proof of financial responsibility before a permit for operation of a hazardous waste disposal facility may be issued.
18 AAC 60.220-240	Requires a Solid Waste Disposal Permit to control or eliminate detrimental health, environmental, and nuisance effects of improper solid waste disposal practices and to operate a solid waste disposal facility.
18 AAC 60.520	General requirement for containment structures used for disposal of drilling wastes.
18 AAC 72	Requires a Wastewater Disposal Permit in order to prevent water pollution (and public health problems) due to unsafe wastewater disposal systems and practices.
18 AAC 75	Provides for oil and hazardous substance pollution control including oil discharge contingency plan (18 AAC 75.305-.395).
18 AAC 75.005-025	Requirements for oil storage facilities for oil pollution prevention.
18 AAC 75.065-075	Requirements for oil storage tanks and surge tanks.
18 AAC 75.080	Facility piping requirements for oil terminal, crude oil transmission pipeline, exploration, and production facilities.
DGC	
AS 44.19.155	Establishes and empowers the Alaska Coastal Policy Council.
AS 46.40	Establishes the Alaska Coastal Management Program.
6 AAC 50	Requires the sale to be consistent with the ACMP, including approved district programs.
6 AAC 80.070(b)(3)	Requires that facilities be consolidated to the extent feasible and prudent.
6 AAC 80.070(b)(10)	Requires that facilities be sited to the extent feasible and prudent where development will necessitate minimal site clearing, dredging, and construction.
6 AAC 80.070(b)(11) and(12)	Requires that facilities be sited to the extent feasible and prudent to allow for the free passage and movement of fish and wildlife.
6 AAC 80.130(c)(3)	Requires that wetlands and tideflats be managed to assure adequate water flow, avoid adverse effects on natural drainage patterns, and the destruction of important habitat.
6 AAC 85	Establishes guidelines for district coastal management programs.
AS 26.23.195	Establishes the State Emergency Response Commission.
AS 39.50.20	Establishes Hazardous Substance Spill Technology Review Council within State Emergency Response Commission for research, testing spill technologies, and to serve as a clearinghouse for containment and cleanup technology.

AS 24.20.600	Citizens Oversight Council established a five-member council to serve as watchdog of state and federal agencies having responsibility for prevention of and response to oil spills, to help ensure compliance with environmental laws and regulations

NSB

19.06 - 19.70.060	North Slope Borough land management regulations, planning, and permitting powers.

Federal Laws and Regulations

Clean Water Act (CWA) - 33 U.S.C. §§ 1251-1387

§ 1343 - Corps permit required to excavate, fill, alter, or modify the course or condition of navigable or U. S. waters.
§ 1344 – Discharge of Dredge and Fill

Oil Spill and Hazardous Substances Pollution Contingency Plan - 40 C.F.R. § 300

EPA Regulations - 40 C.F.R.

§ 109 - Criteria for Oil Removal Contingency Plans
§ 110 - Discharge of Oil
§ 112 - Oil Pollution Prevention. 112.7 - Guidelines for implementation of SPCC plan
§ 113 - Liability Limits for Small Onshore Oil Storage Facilities
§ 114 - Civil Penalties for Violation of Oil Pollution Regulations
§ 116 - Designation of Hazardous Substances
§ 117 - Determination of Reportable Quantities for Hazardous Substances

Coast Guard Regulations - 33 C.F.R.§§ 153-157 Oil Spill Regulation

§ 153 - Reporting Oil Spills to Coast Guard
§§ 155-156 - Vessels in Oil Transfer Operations

Water Quality:

EPA Regulations - 40 C.F.R.

§ 121 - State Certification of Activities Requiring a Federal Permit
§ 136 - Test Procedures for Analysis of Pollutants

NPDES Permit System:

EPA Regulations - 40 C.F.R.

§ 122 - NPDES Permit Regulations
§ 125 - Criteria and Standards for NPDES Permits
§ 129 - Toxic Pollutant Effluent Standards
§ 401 - General Provisions for Effluent Guidelines and Standards
§ 435.10-435.12 - Offshore Oil & Gas Extraction Point Source Category

Ocean Dumping:

EPA Regulations - 40 C.F.R.

§§ 220-225, 227-228 - Ocean Dumping Regulations and Criteria

5 AAC 95.420-430	Requires a Special Area Permit for certain activities within a special area, defined as a state game refuge, a state game sanctuary, or a state fish and game critical habitat area.
AOGCC	
AS 31.05.005	Establishes and empowers the Alaska Oil and Gas Conservation Commission.
AS 31.05.030(d)(9)	Requires an oil and gas operator to file and obtain approval of a plan of development and operation.
AS 46.03.900(35)	Definition of waters.
AS 46.03.100	Accumulation, storage, transportation and disposal of solid or liquid waste standards and limitations.
20 AAC 25.005-570	Requires a permit to drill to help maintain regulatory control over the drilling and completion activities in the state.
20 AAC 25.140	Requires a Water Well Authorization to allow abandoned oil and gas wells to be converted to freshwater wells and to assure there is no contamination of the fresh water source.
ADEC	
AS 46.03	Provides for environmental conservation including water and air pollution control, radiation and hazardous waste protection.
AS 46.03.100	Requires solid waste disposal permits.
AS 46.03.759	Establishes the maximum liability for discharge of crude oil at $500 million.
AS 46.03.900(35)	Definition of waters.
AS 46.04.010-900	Oil and Hazardous Substance Pollution Control Act. This act prohibits the discharge of oil or any other hazardous substances unless specifically authorized by permit; requires those responsible for spills to undertake cleanup operations; and holds violators liable for unlimited cleanup costs and damages as well as civil and criminal penalties.
AS 46.04.030	Requires lessees to provide oil discharge prevention and contingency plans (C-plans). Also, provides regulation of above-ground storage facilities with over 5,000 bbl of crude oil or 10,000 bbl of non-crude oil.
AS 46.04.050	Exemption for above-ground storage facilities for under 5,000 bbl of crude oil or 10,000 of non-crude oil.
18 AAC 15	Requires a Certificate of Reasonable Assurance (Water Quality Certification) in order to protect the waters of the state from becoming polluted. Assures that the issuance of a Federal Permit will not conflict with Alaska's Water Quality Standards.
18 AAC 50	Provides for air quality control including permit requirements, permit review criteria, and regulation compliance criteria.

EPA Regulations - 40 C.F.R.

§ 230 - Discharge of Dredged or Fill Material into Navigable Waters
§ 231 - Disposal Site Determination

Army Corps of Engineers (Corps) Regulations - 33 C.F.R.

§ 209 - Navigable Waters
§§ 320-330 - Permit Program Regulations
§ 323 - Discharge of Dredge and Fill

The Fish and Wildlife Coordination Act - 16 U.S.C. §§ 661-666(c)

Allows comment on § 404 permit applications by USF&WS, NMFS, and EPA.

Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) 42 U.S.C. §§ 9601-9675

EPA Plans - 40 C.F.R.

§ 300 - National Oil and Hazardous Substances Pollution Contingency Plan

Safe Drinking Water Act - 42 U.S.C. § 300

EPA Regulations - 40 C.F.R.

§ 144 - Permit Regulations for the Underground Injection Control Program
§ 146 - Criteria and Standards for Underground Injection Control Program
§ 147 - State Underground Injection Control Program

Coastal Zone Management Act (CZMA) - 16 U.S.C. §§ 1451-1464

NOAA Regulations - 15 C.F.R.

§ 930 - Federal Consistency with Approved Coastal Management Programs
§ 931 - Coastal Energy Impact Program

Solid Waste Disposal Act, as amended by Resource Conservation and Recovery Act (RCRA) - 42 U.S.C. §§ 6901-6991

Clean Air Act (CAA) - 42 U.S.C. §§ 7401-7642

Toxic Substances Control Act - 15 U.S.C. §§ 2601-2655

National Ocean Pollution Planning Act - 33 U.S.C. §§ 1701-1709

National Environmental Policy Act (NEPA) - 42 U.S.C. §§ 4321-4347

Council on Environmental Quality (CEQ) Regulations - 40 C.F.R.

§§ 1500-1508 - Implementing NEPA Procedures

Endangered Species Act (ESA) - 16 U.S.C. §§ 1531-1543

USF&WS Regulations - 50 C.F.R.

§ 17 - Endangered & Threatened Species
§ 402 - Interagency Cooperation

Fish and Wildlife Coordination Act - 16 U.S.C. §§ 661-666(c)

Marine Protection, Research and Sanctuaries Act - 33 U.S.C. §§ 1401-1445

Marine Mammal Protection Act - 16 U.S.C. §§ 1361-1407

Migratory Bird Treaty Act - 16 U.S.C. §§ 703-711

National Historic Preservation Act - 16 U.S.C. § 470

Leases and Permits on Restricted Properties - 25 C.F.R. § 162

Appendix J:

A Method of Addressing Economic Irreversibility

We discuss here an example of calculating the economic cost of long-term or irreversible environmental changes. The method is broadly applicable to the North Slope and beyond; the example of the Arctic National Wildlife Refuge was chosen because it is the only part of the region for which suitable data are available. Chapters 7 and 9 describe physical and biotic effects of seismic exploration and their human effects. Here, the long-term economic costs are considered.

From an economic perspective, damage done to the tundra by seismic explorations and road and pad building is basically economically irreversible. This means that roads, pads, and seismic tracks laid down today are visually very evident for many decades later, as are other long-lived human interventions. Even if an effect does not last forever in a physical sense, it is an economic irreversibility in practice if it lasts foras long as, say, 50. The present value of a dollar every year forever differs by $.002 from the present value of a dollar every year for 50 years at the U.S. Geological Survey's (USGS) use of a 12% rate of interest when analyzing the value of oil in the Arctic National Wildlife Refuge.

Irreversibility is an important ingredient for the accumulation of an effect because the decision to invest in exploration produces visual effects year after year even if no development follows.

Most economic analysis assumes that one readily can undo what one has done. Thus the prospect of irreversibility raises a major concern and requires analysis of the significance of the amount of development and whether development should be prohibited in areas of special value. The following example, calculated using the Arctic National Wildlife Refuge as the example, illustrates an approach for thinking about irreversible accumulated effects. Data on environmental costs would have to be collected to reach a confident conclusion. It does not include any non-economic factors that usually also influence such decisions.

ALL OR NONE?

One piece of relevant data for policy making is how much oil is *economically*, not technically, recoverable in an area. As an example, Figure J-1 illustrates the amount of oil recoverable from the refuge's 1002 Area as a function of price. A price less than $15 per barrel ($0.36 per gallon), makes oil development in the Arctic National Wildlife Refuge unprofitable. If the belief is that $25 per barrel ($0.60 per gallon) will prevail, then the gross value of oil in the refuge would be more than $130 billion if it were extracted and sold today. The cost per barrel in

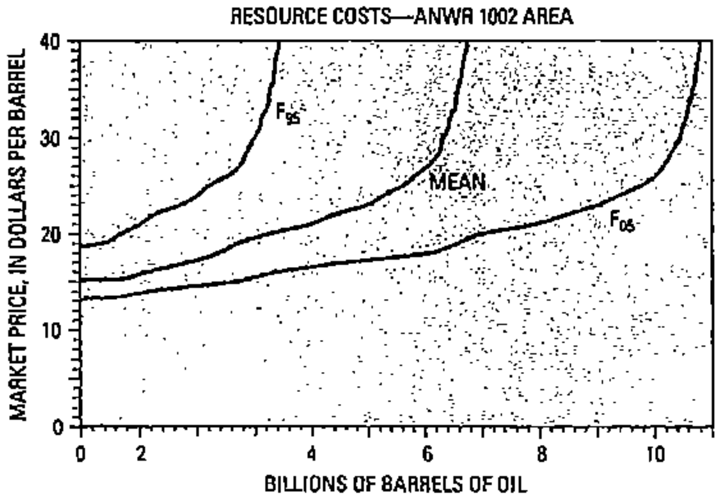


FIGURE J-1. Summary of the USGS estimates of economically recoverable oil that may occur beneath the Federal 1002 Area of the Arctic National Wildlife Refuge. The three curves are based on estimates of economically recoverable oil volumes at the mean (expected value, and at the 95 % (F95) and 5 % (F05) probabilities. Each curve relates market price/cost to the volume of oil estimated to be profitably recoverable. Included are the costs of finding, developing, producing, and transporting oil to market based on a 12 % after-tax return on investment all calculated in constant 1996 dollars. Source: USGS 1999.

Figure J-1 represents discovery, developing, production, and transport costs. The curve should be shifted up for other costs left out, particularly the expected costs due to oil spills, decommissioning, and other environmental damages that can be expressed on a per barrel basis.

The relation of prices and quantities of oil in Figure J-1 provides an estimate of net benefits from extracting oil in the Arctic National Wildlife Refuge as of today and depends on the prevailing price of oil. The figure portrays the incremental or marginal costs of oil. From this, total cost can be calculated. It is the area under the (mean) curve up to a particular quantity of oil. Total revenue is just the product of price and quantity, from which total cost is subtracted to yield a net benefit exclusive of environmental costs for any given expected price.

The expected future price of oil plays a vital role in the evaluation of a "go" or "no go" decision. Figure J-2 illustrates the price of oil per barrel historically. The price of oil is not determined in the market because the oil market is not competitive now. Economists characterize the oil market as a monopoly with a competitive fringe. The Organization of Petroleum Exporting Countries (OPEC) is a collection of nations who seek to control price through collusion. When collusion is successful, the OPEC has driven the price of oil above $35 a barrel ($0.83 per gallon) in the past. However, it has not been possible to successfully collude for very long. The free market, competitive price is believed to be $10 a barrel ($0.24 per gallon), according to the oil minister for Kuwait (NYT, 11/16/01, p.c2)

The ability of the oil-producing countries to collude plays a key role in the potential development of an area. If the chance of persistent collusion is low, a resulting low market price of oil will preclude development.

The second key factor in evaluating development is environmental costs. Among potential environmental costs we focus here on the irreversible nature of the visual impact created by seismic trails, roads and pads. These costs can be treated as the fixed social costs of oil development, which occur at the time of development. It will be assumed that people in general are not pleased with these seismic trails and the imprint of roads and pads, and that they would be willing to pay in principle, to keep them from occurring. One should think of this as an "as if" proposition. It is not that people actually would be asked to pay but rather people are asked to express displeasure in money terms. The thought experiment resembles what we do when we visit a restaurant and express expected gustatory pleasure in money terms by the choices made or not made.

TWO SCENARIOS

The crux question is whether the expected private *net* revenue from oil development, for which there are estimates, exceeds the social cost. Since no such costs have been estimated, a threshold analysis has to be made. Put another way, what is the least amount of money a representative family in the U.S. must be willing to pay annually to make the losses from development exceed the benefits of development?

Two scenarios are developed, one where the interest or discount rate is 12%, following the assumptions of the USGS in estimating the incremental costs of development. The other is a discount rate of 4% which is more in line with what the economics profession would advocate for long lived investment projects (Weitzman 2001).

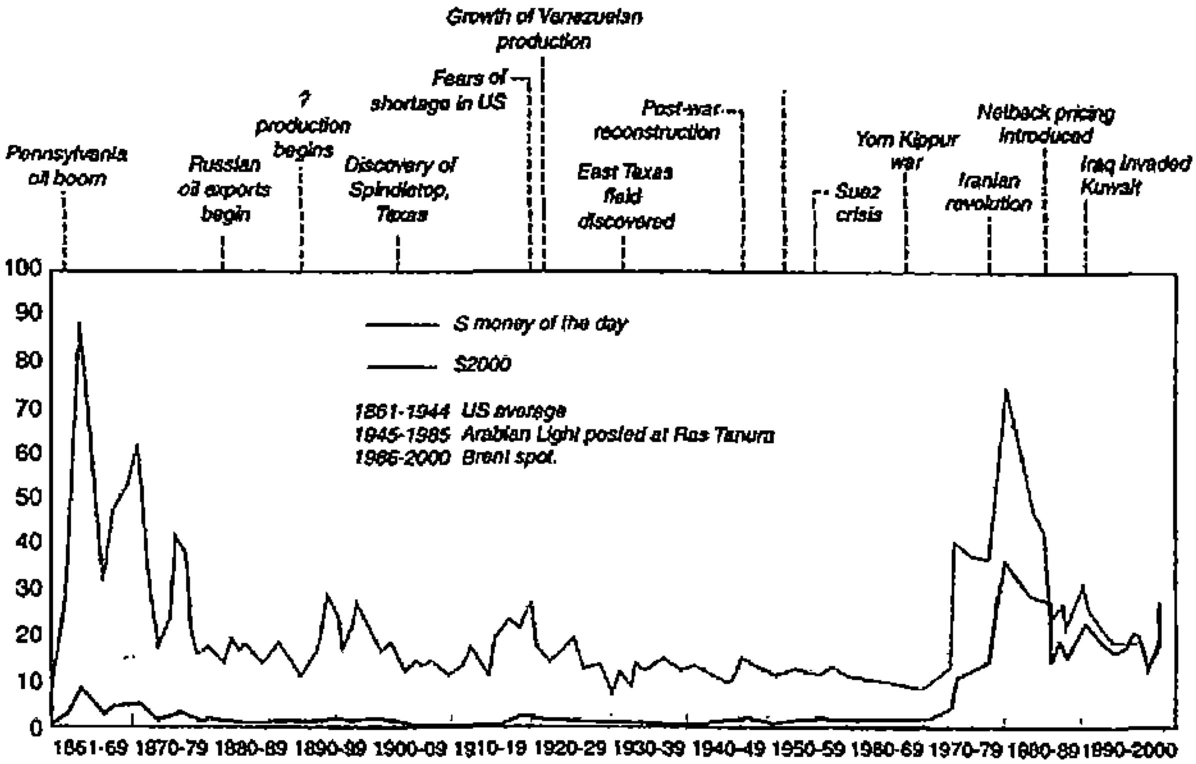


Figure J-2. Source: BP Exploration 2001b

Extraction is not an instantaneous decision. The land must be opened for leasing. It takes time to consummate actual discovery. Facilities have to be built. This process will take 7-12 or more years based on past experience. Here we assume that it takes 10 years before the first field actually produces.[1] Further we assume that it will take 40 years for the oil resources to be depleted.[2] New fields will come on line roughly in decreasing profitability. The extraction period cannot be shortened very much because this reduces the total amount of oil that can be extracted and reduces overall profit to the owner (the public). Prudhoe Bay has been extracting for 24 years and oil specialists expect there are more than 10 years of future productivity. The U.S. Department of Energy expects a total productive life of 65 years with a peak at 18 or 22 years depending on rates of development (DOE). This assumption plays an important role in the economic analysis below. To simplify the analysis, assume that all the oil is extracted at the mid-point of the extraction period—20 years—and that value and costs are discounted back to the present, taken to be 10 years from now. A shorter extraction period entails less discounting and a higher profit from oil development. Discounting back to the actual present reduces the values by one-third.

In the calculations that follow, an exponential function represents the incremental cost curve of the USGS (See Figure J-1).

The estimated incremental or marginal private cost functions (MC) is[3]

$$MC = 0.611Q^{1.725} + 15.$$

Table J-1 is an auxiliary table illustrating the lump sum value of the environment necessary to equal the value of oil development in the Arctic National Wildlife Refuge for three alternative assumptions about the possible prices, conditioned on collusion occurring and two interest rates.

Table J-1 Net value (2011) of Oil Production in the Arctic National Wildlife Refuge Present Value 2011 dollars (billions)

	Interest rate = .12 Price			Interest rate = .04 Price		
Prob of Collusion	20	25	40	20	25	40.
¼	.24	.73	2.1	1.20	3.59	15.28
½	.49	1.4	6.2	2.40	7.9	30.56
¾	.7	2.18	9.3	3.61	10.78	45.84

The formula for calculating this table is the weighted probability of expected net revenues in present value (2011) terms.

[1] The basis for the calculation assumes no lags due to litigation by environmental interests and perhaps others. A lag increases the likelihood that oil development is not economically feasible.

[2] President Bush recently spoke in terms of 47 years (NYT 5/18/01). The longer the depletion period, the more distant are the revenues, so the less valuable is the field, for a given total volume.

[3] A c++ program was written to fit Figure J-1 and close to 600 data points were drawn. A software package, "Kaleida Graph," transformed the data points into the function.

$$E\hat{V}(\overline{P}) = \left\{\overline{P}Q(\overline{p}) - \int_0^{\overline{Q}(\overline{p})} 0.611Q^{1.725}dQ - 15Q\right\}e^{-rt}(1-\Pi) + \underline{P}\Pi e^{-rt}$$

where $E\hat{V}(\overline{P})$ = expected net present value of oil production in the Arctic Refuge excluding environmental costs

$1-\Pi$ = the probability of successful collusion

$\underline{P} = 0$ because competition drives price below $15 per barrel. See text.

$Q(\overline{P})$ = USGS estimate of oil volume when $P = \overline{P}$.

r = the interest rate.

Explaining the equation in greater detail, when the price is high, $\overline{P}$, with probability (1-Π), the revenue is $\overline{P}Q(\overline{P})$, where $Q(\overline{P})$ is computed from the equation for MC. When the price is low, P̲, with probability Π, there are no revenues because P̲ is the competitive price and is too low to warrant extraction. So the expected revenue is

1) Exp Rev = $\overline{P}Q(\overline{P})(1-\Pi)$.

The private cost = 0, when no oil is extracted, with probability Π. The private cost, when there is extraction is the area under the marginal cost curve in Figure J-1,

2) Exp. Cost = $\int_0^{\overline{Q}(\overline{p})} 0.611Q^{1.725} + 15Q$

which occurs with probability 1 - Π. The expected net revenue is the difference between expected revenue and cost = the difference between equations (1) and (2). The term, e^{-rt}, discounts the expected net revenue back to 2011 from 2031, where the latter date is the midpoint of the extraction period.

The net present value (at a 12% interest rate) at the time extraction is assumed to begin, when the chance of collusion is ½ and it achieves a price of $25 per barrel ($0.60 per gallon), is $1.45 billion. To match this development value requires a lump sum preservation value per family, of about $14.50 since there are about 100 million families in the U.S. This is less than one-half the value people were willing to pay to avoid another Exxon-Valdez oil spill for 10 years, according to a study done for the state of Alaska. (See Carson et al. 1992)

To capture the idea that some environmental costs are economically irreversible, together with any other credible irreversible environmental cost, it is appropriate to express the threshold environmental values on an annual basis as in Table J-2. If there is a 50% chance of colluding and this market structure could achieve a price of $20 or $25 per barrel ($0.48 or $0.60 per gallon), then a willingness-to-pay of about $ .96 or 2.87 annually per family in the U.S. would be necessary to match the value of oil development in the Arctic National Wildlife Refuge at a 4% rate of interest or $ .58 to $1.74 annually at the 12% rate of interest used by USGS. Expressed in present day values rather than 2011 values for the 50% chance of $25 per barrel ($0.60 per gallon), the threshold values per family are about $1.89 or $1.15 annually respectively for interest rates of 4 or 12% (Table J-3).

Table J-2 Per Family Net Value of Oil Production Arctic National Wildlife Refuge (2011 dollars)
$r = 0.12$ and $t = 20$

Probability of Collusion	Price		
	20	25	40
¼	2.43	7.26	30.85
½	4.86	14.51	61.70
¾	7.28	21.77	92.55

Per Family Net Value of Oil Production Arctic National Wildlife Refuge (2011 dollars)
$r = 0.04$ and $t = 20$

Probability of Collusion	Price		
	20	25	40
¼	12.02	35.94	152.79
½	24.05	71.87	305.59
¾	36.07	107.81	458.38

Table J-3 Annual Family Willingness to Pay (2011 dollars)
$r = 0.12$ and $t = 20$

Probability of Collusion	Price		
	20	25	40
¼	0.29	0.87	3.70
½	0.58	1.74	7.40
¾	0.87	2.61	11.11

Annual Family Willingness to Pay (2011 dollars)
$r = 0.04$ and $t = 20$

Probability of Collusion	Price		
	20	25	40
¼	0.48	1,44	6.11
½	0.96	2.88	12.22
¾	1.44	4.31	18.34

If the extraction period were shorter, the threshold willingness to pay would increase as would be the case if more oil was economically available. A lower threshold willingness-to-pay would follow if seismic trails were laid down before extraction began and to the extent that there are other expected environmental costs associated with oil extraction not included in these assumed costs.

Appendix K:

Biosketches of the Committee's Members

COMMITTEE ON CUMULATIVE ENVIRONMENTAL EFFECTS OF ALASKAN NORTH SLOPE OIL AND GAS ACTIVITIES

GORDON ORIANS (Chair) is Professor Emeritus of Zoology at the University of Washington, Seattle. He received his Ph.D. in zoology from the University of California at Berkeley. He has been a member of the faculty of the University of Washington since 1960 and served as Director of its Institute of Environmental Studies from 1976 to 1986. He was elected to the National Academy of Sciences in 1989. His research interests include the evolution of vertebrate social systems, territoriality, habitat selection, and environmental quality. He is a past president of the Ecological Society of America, a member of the American Academy of Arts and Sciences, and a foreign member of the Royal Netherlands Academy of Sciences. He has served as chair of the Board on Environmental Studies and Toxicology since 1997, as a member of the NRC's Report Review Committee, and as chair or member of many other NRC committees and commissions.

THOMAS F. ALBERT has recently retired from duties as Senior Scientist in the Department of Wildlife Management, North Slope Borough, Barrow, AK. He now serves as Senior Scientist with Wag-Hill Arctic Science, LLC. He received a B.S. from the Pennsylvania State University, V.M.D. from the University of Pennsylvania, and Ph.D. in biology from Georgetown University. He is a Fellow of the Explorers Club (New York) and the Arctic Institute of North America and is an honorary member of the Barrow Whaling Captains Association. His major areas of interest are arctic wildlife, environmental biology, and veterinary medicine. He has experience regarding the importance of bowhead whales to the Eskimo people of northern Alaska and the impacts of oil and gas industry activities on whale behavior and habitat.

GARDNER BROWN is a Professor of Economics, specializing in natural resource economics, non-market valuation, and applied microeconomic theory, at the University of Washington, Seattle. He received his Ph.D. from the University of California, Berkeley (1964). Dr. Brown serves on the editorial board of *Environment and Development Economics* and the *Journal of Environmental Economics and Management*.

RAYMOND CAMERON earned a Ph.D. in Zoophysiology from the University of Alaska (1972). He served as Wildlife Biologist for the Alaska Department of Fish and Game for twenty years (1974-94) and is currently Affiliate Professor of Wildlife Biology at the Institute of Arctic Biology, University of Alaska Fairbanks. Dr. Cameron has published extensively on the behavioral, nutritional, and reproductive consequences of petroleum development.

PATRICIA A. L. COCHRAN is the Executive Director of the Alaskan Native Science Commission. She is an Inupiat Eskimo born and raised in Nome, Alaska. Previously she served as administrator of the Institute for Circumpolar Health Studies at the University of Alaska Anchorage; Executive Director of the Alaska Community Development Corporation; Local Government Program Director with the University of Alaska Fairbanks; and Director of Employment and Training for the North Pacific Rim Native Corporation. Ms. Cochran served on the NRC Committee on Management of Wolf and Bear Populations in Alaska.

S. CRAIG GERLACH is an Associate Professor of Anthropology at the University of Alaska Fairbanks. He earned his Ph.D. in anthropology from Brown University (1989). His areas of expertise include archaeology of pastoralists, arctic hunter-gatherers, zooarchaeology, and quaternary paleoecology; arctic oil and gas activities; Native American archaeology and subsistence studies; historic archaeology and anthropology of reindeer herding in Northwest Alaska; analysis of both archaeological and historical resources, as well as subsistence studies on the North Slope and along the TAPS route. He has twenty years of experience involving academic researchers, the native community, the oil and gas industry, and mining companies in the fields of archaeology and cultural anthropology.

ROBERT B. GRAMLING is a Professor of Sociology and Director of the Center for Socioeconomic Research at the University of Southwestern Louisiana in Lafayette. He earned a B.S. in Social Welfare (1965), M.S. in Social Science (1967), and Ph.D. in Sociology (1975) from the Florida State University. His areas of interest include environmental sociology—natural resource development, social impact assessment, and risk assessment. Dr. Gramling is the Principal Investigator for the Louisiana Applied Oil Spill Research and Development Program's study on the "Production and Analysis of an Oil Spill Database for Louisiana" (1999-2001). He is currently the Associate Editor for *Society and Natural Resources* and serves on the Standing Scientific Committee, Gulf of Mexico Fisheries Management Council (1994-present) and National Marine Fisheries Service/Northwest Power Planning Council, Independent Scientific Advisory Board (1999-present). Formerly he served on the Study of the Economic, Social, and Psychological Impacts of the Exxon Valdez Oil Spill (1990-1991); NRC Committee to Evaluate Information Adequacy for the Presidential Task Force on Outer Continental Shelf leasing in Florida and California (1989-1990); and NRC Committee to Review the Department of Interior, Outer Continental Shelf Environmental Studies Program: Socioeconomic Panel (1988-1991). Dr. Gramling has published several books on off-shore oil development including: *Oil on the Edge: Offshore Development, Conflict, Gridlock* (1996) and *Oil in Troubled Waters: Perceptions, Politics, and the Battle Over Offshore Drilling* (1994).

GEORGE GRYC is a geologist, recently retired from the U.S. Geological Survey. He received his M.S. from the University of Minnesota (1941). He has conducted field studies in northern Alaska in support of the U.S. Navy's war-time program to explore Naval Petroleum Reserve. From 1950 to 1960, he was Chief of the USGS, Navy Oil Unit. From 1960 to 1963, he was Staff Geologist to the Chief Geologist, USGS, in the Office of Regional Geology that included geologic studies in Alaska. From 1963 to 1976, Dr. Gryc was Chief of the Alaskan Branch, Geologic Division, in the USGS Regional Center in Menlo Park, California, which was the main operational unit for all USGS mineral, energy and geologic studies in Alaska. In 1976 has was appointed Regional Geologist for the Western Region. From 1976 to 1985, he was head of the new USGS unit, "Office of National Petroleum Reserve, Alaska," ONPRA, in the USGS

Director's Office. As Chief ONPRA, he was in charge of all geological, geophysical, and drilling activities in NPRA. From 1982 to 1995, he was the Director's Representative for the Western Region. Mr. Gryc retired from full-time service in January 1995, but continued USGS activities as a volunteer, first as a Pecora Fellow and now as a Scientist Emeritus. He has served on several NRC committees on permafrost.

DAVID M. HITE is a geological consultant. He earned his M.S. and Ph.D. in Geology from the University of Wisconsin. Dr. Hite has worked most recently as a Geological Consultant for a variety of companies and Alaskan Native Corporations. He has experience in prospect, play and basin analysis in frontier areas (Alaska, Arctic Canada, and OCS) and has been involved in numerous research, exploration, and development activities including: basin evaluation; development of depositional models for sandstone reservoirs; homogeneity/heterogeneity studies of reservoir horizons; and the development of numerous surface geological field programs.

MAHLON C. KENNICUTT, II is Director of the Geochemical and Environmental Research Group in the College of Geosciences at Texas A&M University and a member of the graduate college faculty at the College of Geosciences & Maritime Studies. He received his Ph.D. in oceanography from Texas A&M University (1980). His research interests are in marine chemistry, organic geochemistry, the chemistry of contaminants in the environment, the design and implementation of environmental monitoring programs, the fate and affect of xenobiotic chemicals in the environment, and the development of integrated indicators of ecosystem health. Dr. Kennicutt has significant Antarctic experience, and has participated in 35 ocean research cruises over the past 20 years. He assisted in organizing and writing the workshop report, "Monitoring of Environmental Impacts from Science and Operations in Antarctica," July 1996. Dr. Kennicutt is one of the two U.S. delegates to the Scientific Committee on Antarctic Research (SCAR). He serves on the SCAR Group of Specialists on Environmental Affairs and Conservation and SCAR Group of Specialists on Subglacial Lakes, where he has been key in developing the international science plan for exploration of subglacial lakes.

ARTHUR H. LACHENBRUCH is a Geophysicist Emeritus at the U.S. Geological Survey. He received his B.A. from the Johns Hopkins University (1950), and M.A. (1954) and Ph.D. (1958) in geophysics from Harvard University. He is interested in problems of temperature and stress in the solid earth on a variety of scales ranging from ice-wedge polygons in permafrost to continental tectonics. In 1963, he received the Geological Society of America's Kirk Bryan Award for Geomorphology, and in 1989 the American Geophysical Union Walter H. Bucher Medal for contributions to knowledge of the Earth's crust. Dr. Lachenbruch is also interested in applications to environmental issues such as design of the Trans Alaska Pipeline, implications of borehole temperatures for 20th century climate change, and issues of "sustainability." He has conducted many years of field studies on the North Slope and elsewhere in Alaska, and has served on the Polar Research Board and NRC committees and on science advisory panels for many groups including the Arctic Institute of NA, Los Alamos National Laboratories, U.S. Geological Survey, AEC, University of Alaska, National Aeronautics and Space Administration, and American Association of Petroleum Geologists. He was elected to the National Academy of Sciences in 1975.

LLOYD F. LOWRY is an Affiliate Associate Professor at the University of Alaska School of Fisheries and Ocean Sciences. Previously he was the Statewide Program Coordinator of the

Marine Mammal Division of Alaska's Department of Fish and Game. Mr. Lowry received a B.S. in biology from Southeastern Massachusetts University (1971) and M.S. in marine sciences from the University of California, Santa Cruz (1975). He has extensive experience analyzing human impacts on marine mammals and their habitats in the Beaufort Sea. Mr. Lowry is Chairman of the Marine Mammal Commission's Committee of Scientific Advisors. He has published extensively on seals and other marine mammals and has served on the NRC Committee on the Bering Sea Ecosystem.

LAWRENCE L. MOULTON is the owner of and Senior Fisheries Biologist at MJM Research. He earned his B.S. (1969), M.S. (1970), and Ph.D. (1977) in Fisheries Biology at the University of Washington. His areas of expertise include fishery biology, aquatic biology, and ichthyology. Dr. Moulton has over 25 years experience in North Pacific and Alaskan fisheries investigations. He has managed many studies on freshwater, anadromous, and marine fisheries and the effects of harvest or habitat alteration on aquatic populations. These studies have ranged from large, multidisciplinary field and analytical studies to specialized mitigation and risk analyses. He has also served as an expert witness in arbitration and litigation cases and has been an invited speaker at a variety of symposia and workshops on anadromous, marine, and estuarine fishes.

EVELYN (CHRIS) PIELOU is a retired professor of ecology. She earned a B.S. (1951), Ph.D. (1962) and D.Sc. (1975) from the University of London. Dr. Chris Pielou was a Research Scientist for the Canadian Dept. of Forestry (1963-64); Research Scientist at the Dept. of Agriculture (1964-67); Professor of Biology at the Queen's University, Kingston (1968-71); Killam Research Professor at Dalhousie University, Halifax (1971-74); Professor of Biology, Dalhousie University (1974-81); and Oil Sands Environmental Research Professor at the University of Lethbridge (1981-86). Dr. Pielou is the author of numerous books including: *Introduction to Mathematical Ecology* (1969); *Population and Community Ecology* (1974); *Ecological Diversity* (1975); *Mathematical Ecology* (1977); *Biogeography* (1979); *Interpretation of Ecological Data* (1984); *The World of Northern Evergreens* (1988); *After the Ice Age: The Return of Life to Glaciated North America* (1991); *A Naturalist's Guide to the Arctic* (1994); *Fresh Water* (2000); and *The Energy of Nature* (2001). Other writings include over 60 papers, articles and scientific publications. Dr. Pielou's work has been recognized by several awards including: Fellow, Royal Society of Arts; recipient George Lawson medal of Canadian Botanical Association (1984); Eminent Ecologist Award of Ecological Society of America (1986); Distinguished Statistical Ecologist Award of the International Congress of Ecology (1990); Honorary LL.D. from Dalhousie University (1993); Foreign Honorary Member of the American Academy or Arts and Sciences; Honorary Life Member of the British Ecological Society; and Honorary Sc.D. from the University of British Columbia (2001).

JAMES S. SEDINGER is a Professor in the Department of Environmental and Resource Sciences at the University of Nevada Reno. He is the former Interim Director of the Institute of Arctic Biology and Professor of Wildlife Ecology at the University of Alaska Fairbanks. Dr. Sedinger received his Ph.D. from the University of California, Davis (1983). He is an ornithologist that has worked and published for years on black brant throughout Alaska. His professional interests are in the study of life-histories, population biology, and nutritional ecology of avian species, particularly waterfowl. Before becoming a professor at the University of Alaska Fairbanks, he worked for the U.S. Fish and Wildlife Service as a research wildlife biologist. He is a member of numerous professional organizations, including the American Association for the Advancement of Science and the Ecological Society of America.

K. JUNE LINDSTEDT-SIVA is a Senior Consultant at ENSR Consulting and Engineering (1996-present). She earned her A.B. (1963), M.S. Biology (1967), Ph.D. (1971), in Biology at the University of Southern CA, Los Angeles. Her areas of expertise include oil spills fate and effects; response technology; response planning; cleanup methods; dispersant fate and effects; dispersant use planning; dispersant application technology; spill management/decision making, endangered species/biodiversity, sustainable development, biomonitoring, and arctic, temperate, and tropical marine and terrestrial environmental planning. Formerly, she was the Manager of Environmental Protection, ARCO, Los Angeles (1986-96) and worked for Atlantic Richfield, Los Angeles as Manager of Environmental Sciences (1981-86), Senior Science Advisor (1977-81) and Science Advisor (1973-77). She was a member of the NRC Polar Research Board (1993-1996) and served on the NRC Alaska Outer Continental Shelf Panel (1992-1994). She is a member of the Advisory Council, National Institutes for the Environment (1992-1995) and EPA's Panel on Evaluation of Bioremediation as an Oil Spill Response Method (1991-1992). She also served on the National Science Board (1984-1990 and several NSB committees, including the Committee on NSF Role in Polar Regions. She participated in API sponsored research on the fate and effects of oil spills, effects and effectiveness of spill response technologies, and spill response planning, chairing several task forces. Additionally, she was chairman of the ASTM Task force on Dispersant Use Guidelines for the Treatment of Oil Spills (1980-1986).

LISA SPEER is a Senior Policy Analyst and co-director of the Oceans Program at the Natural Resources Defense Council. She earned her M.S. in Forest Science at Yale University. Her work has focused on marine fisheries and on oil and gas development on the U.S. continental shelf and the Alaskan North Slope. She served on the NRC Committee on Marine Environmental Monitoring and is a member of the NRC Board on Environmental Studies and Toxicology.

DONALD (SKIP) WALKER is a Professor at the University of Alaska Fairbanks. He earned his Ph.D. in Environmental Biology from the University of Colorado, Boulder (1981). Dr. Walker is a scientific expert on the cumulative impacts of oil-field disturbance on Alaska North Slope landscapes and long-term recovery of vegetative communities in these communities. His research interests include tundra ecology, vegetation mapping methods, landscape ecology, quantitative ecology methods, vegetation of northern Alaska, snow-ecosystem interactions, hierarchical geographic information systems, and disturbance and recovery of arctic ecosystems.

References

Aagaard, K. 1984. The Beaufort undercurrent. Pp. 47-71 in The Alaskan Beaufort Sea: Ecosystems and Environments, P.W. Barnes, D.M. Schell, and E. Reimnitz, eds. Orlando: Academic Press.

Abdelnour, R., Y. Gong, and G. Comfort. 2000. Ice booms for oil spills recovery in ice infested waters. Proceedings, International Oil and Ice Workshop 2000: Oil Spill Preparedness and Response for Cold Climates, April 5-7, 2000, Anchorage & Prudhoe Bay, Alaska. CD-ROM. Alaska Clean Seas.

Abele, G., J. Brown, and M.C. Brewer. 1984. Long-term effects of off-road vehicle traffic on tundra terrain. Journal of Terramechanics 21(3):283-294.

Abele, G., D.A. Walker, J. Brown, M.C. Brewer, and D.M. Atwood. 1978. Effects of Low Ground Pressure Vehicle Traffic on Tundra at Lonely, Alaska. CRREL Special Report #78-16. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH. 63 pp.

Abou-Sayed, A.S., D.E. Andrews, and L.M. Buhidma. 1989. Evaluation of Oily Waste Injection Below the Permafrost in Prudhoe Field. SPE 18757. Presented at the Society of Petroleum Engineering California Regional Meeting, April 5-7, 1989, Bakersfield, CA.

Adamczewski, J.Z., C.C. Gates, R.J. Hudson, and M.A. Price. 1987. Seasonal changes in body composition of mature female caribou and calves (*Rangifer tarandus groenlandicus*) on an arctic island with limited winter resources. Can. J. Zool. 65(5):1149-1157.

Adams, L.G., and B.W. Dale. 1998. Reproductive performance of female Alaskan caribou. J. Wildl. Manage. 62(4):1184-1195.

ADEC (Alaska Department of Environmental Conservation). 1985. Information Sheet for Reserve Pit Discharge General Permit. Department of Environmental Conservation, State of Alaska.

ADEC (Alaska Department of Environmental Conservation). 2000. Joint Agency Evaluation of the Spring and Fall 2000 North Slope Broken Ice Exercises. Prepared by Alaska Department of Environmental Conservation, North Slope Borough, Alaska Department of Natural Resources, Minerals Management Service, and U.S. Coast Guard. 47 pp.

ADEC (Alaska Department of Environmental Conservation). 2001a. Contaminated Site Remediation Program Handbook, Department of Environmental Conservation, State of Alaska [Online]. Available: http://www.state.ak.us/dec/dspar/csites/pmhndbk.htm [accessed Dec. 11, 2002].

ADEC (Alaska Department of Environmental Conservation). 2002. Solid Waste Mangement. Division of Environmental Health, Alaska Department of Environmental Conservation [Online]. Available: http://www.state.ak.us/dec/deh/solidwaste/home.htm. [accessed Dec.11, 2002].

ADF&G (Alaska Department of Fish and Game). 1999. Community Profile Database, Vol. 5. Arctic Region. Alaska Department of Fish and Game, Juneau, AK.

ADNR (Alaska Department of Natural Resources). 2000. Annual Report: 2000. Division of Oil and Gas, Department of Natural Resources, State of Alaska.

ADNR (Alaska Department of Natural Resources). 2001a. Summary of State Competitive Lease Sales. Division of Oil and Gas, Department of Natural Resources, State of Alaska [Online]. Available: http://204.126.119.8/oil/products/publications/otherreports/5year99/5year99%5Fsummary.html [accessed Dec. 11, 2002].

ADNR (Alaska Department of Natural Resources). 2001b. Alaska Well Files. Division of Oil and Gas, Department of Natural Resources, State of Alaska. On-line Digital Files. Available: http://www.dog.dnr.state.ak.us/oil/ [accessed April 15, 2002].

AeroMap. 2002. Maps. AeroMap U.S., International Photogrammetric Consultants, Anchorage, AK.

AGRA (AGRA Earth & Environmental, Inc.). 2000. Tundra Spill Cleanup and Remediation Tactics. Second Draft. 0-024-01292-0. Prepared by AGRA Earth & Environmental, Inc., Fairbanks, AK, for Alaska Department of Environmental Conservation, Fairbanks, AK. August 2000.

Ahmaogak, G.N. 1985. Comments regarding the development of a policy pertaining to research in the U.S. Arctic. Inuit Studies 9(2):27-32.

Ahmaogak, G.N. 1986. Formulating U.S. Arctic Research Policy: Recommendations from the North Slope Borough. Pp. 21-25 in Arctic Science Policy and Development: Proceedings, a UNESCO-MAB International Conference, August 28-30, 1985, University of Alaska, Fairbanks, M.M.R. Freeman, and C.W. Slaughter, eds. Washington, DC: U.S. Man and the Biosphere Program.

Ahmaogak, G.N. 1989. Protecting the habitat of the bowhead whale. Pp. 593-597 in Proceedings of the Sixth Conference of the Comité arctique international, 13-15 May 1985, Fairbanks, AK, L. Rey, and V. Alexander, eds. New York: Brill.

Aitchison, C.A. 2001. The effect of snow cover on small animals. Pp. 229-265 in Snow Ecology: An Interdisciplinary Examination of Snow-Covered Ecosystems, H.G. Jones, J.W. Pomeroy, D.A. Walker, and R.W. Hoham, eds. Cambridge: Cambridge University Press.

Alaska Clean Seas. 1999. Alaska Clean Seas Technical Manual. North Slope Atlas. Alaska Clean Seas, Prudhoe Bay, AK, March 1999 [Online]. Available: http://www.asgdc.state.ak.us/maps/cplans/ns/cleanseas/cleanseas.html [accessed Dec. 11, 2002].

Alaska Department of Labor and Workforce Development. 2001. Nonresidents Working in Alaska-1999. Alaska Department of Labor and Workforce Development, State of Alaska, February 1, 2001 [Online]. Available: http://146.63.75.50/research/reshire/nonres.pdf [accessed Dec. 11, 2002].

Alaska Permanent Fund. 2001. Permanent Fund Dividend Program. Alaska Permanent Fund. [Online]. Available: http://http://www.apfc.org/alaska/dividendprgrm.cfm?s=4 [accessed Oct. 24, 2002].

Alaska Regional Assessment Group. 1999. Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change, Alaska. Prepared for the U.S. Global Change Research Program. Center for Global Change and Arctic System Research, University of Alaska, Fairbanks, AK [Online]. Available: http://www.besis.uaf.edu/regional-report/regional-report.html [accessed Dec. 11, 2002].

Albert, T.F., ed. 1981a. Tissue Structural Studies and Other Investigations on the Biology of Endangered Whales in the Beaufort Sea. Final Report for the period April 1, 1980 through June 30, 1981. Prepared for U.S. Department of the Interior, Bureau of Land Management, Alaska OCS Office, by Department of Veterinary Science, University of Maryland, College Park, MD.

Albert, T.F. 1981b. Some thoughts regarding the possible effects of oil contamination on the bowhead whale, *Balaena mysticetus*. Pp. 945-953 in Tissue Structural Studies and Other Investigations on the Biology of Endangered Whales in the Beaufort Sea. Final Report for the period April 1, 1980 through June 30, 1981, Vol. 2., T.F. Albert, ed. Prepared for U.S. Department of the Interior, Bureau of Land Management, Alaska OCS Office, by Department of Veterinary Science, University of Maryland, College Park, MD.

Albert, T.F. 1990. Observations on the socio-economic and cultural concerns of the indigenous people of nothhern Alaska. Pp. 341-351 in Arctic Research and Prospects: Proceedings of the Conference of Arctic and Nordic Countries on Coordination of Research in the Arctic, December 1988, Leningrad, Part 2. Moskow: Nauka.

Albert, T.F. 1996. Overview of the North Slope Borough bowhead whale research with a few comments about industrial activity in the Beaufort Sea area. Pp. 127-130 in Arctic Synthesis Meeting, October 23-25, 1995, Proceedings, K.L. Mitchell et al., eds. MMS 95-0065. NTIS PB97-105449. MBC Applied Environmental Sciences, Inc., Costa Mesa, CA, Mineral Management Service, Anchorage, AK, Alaska Outer Continental Shelf Office.

Albert, T.F. 2001. The influence of Harry Brower, Sr., an Inupiaq Eskimo hunter, on the bowhead whale research program conducted at the UIC-NARL facility by the North Slope Borough. Pp. 265-278 in Fifty More Years Below Zero: Tributes and Mediations for the Naval Arctic Research Laboratory's First Half Century at Barrow, Alaska, D.W. Norton, ed. Calgary, Alberta: Arctic Institute of North America.

Albrecht, S.L. 1978. Sociocultural factors and energy resource development in rural areas of the West. J. Environ. Manage. 7(1):73-90.

Alexander, V., D.C. Burrell, J. Chang, R.T. Cooney, C. Coulon, J.J. Crane, J.A. Dygas, G.E. Hall, P.J. Kinney, D. Kogl, T.C. Mowatt, A.S. Naidu, T.E. Ostercamp, D.M. Schell, R.D. Siefert, and R.W. Tucker. 1974. Environmental Studies of an Arctic Estuarine System. Final Report R-74-1. Institute of Marine Science, University of Alaska, Fairbanks, AK.

Allaye-Chan, A.C. 1991. Physiological and Ecological Determinants of Nutrient Partitioning in Caribou and Reindeer. Ph.D. Dissertation. University of Alaska, Fairbanks, AK.

Allaye-Chan, A.C., R.G. White, D.F. Holleman, and D.E. Russell. 1990. Seasonal concentrations of cesium-137 in rumen content, skeletal muscles and feces of caribou from the porcupine herd: Lichen ingestion rates and implications for human consumption. Pp. 17-24 in Proceedings of the Fifth International Reindeer/Caribou

Symposium, August 18-22, 1988, Arvidsjaur, Sweden, C. Rehbinder, O. Eriksson, and S. Skjenneberg, eds. Rangifer, Spec. Issue No. 3. Harstad, Norway: Nordic Council for Reindeer Research.

Allen, A.A. 1988. Comparison of response options for offshore oil spills. Pp. 289-306 in Proceedings of the 11th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar, June12-14, 1988, Vancouver, BC. Environment Canada, Ottawa, Ontario.

Allen, A.A. 1999. Controlled burning of offshore oil spills. Spiltec, Seattle, WA [Online]. Available: http://www.americanmarine.org/in-situ.html 14 pp. [accessed May 3, 2002].

Allen, A.A. 2000. Response operations at freeze-up and break-up. Proceedings, International Oil and Ice Workshop 2000: Oil Spill Preparedness and Response for Cold Climates, April 5-7, 2000, Anchorage & Prudhoe Bay, Alaska. CD-ROM. Alaska Clean Seas.

Ambrosius, K. 2002. Calculation of Area Impacted by Oil Field Development North Slope Alaska. Memorandum from Ken Ambrosius, AeroMap U.S., to National Academy of Sciences, Washington, DC. January 30, 2002.

Amstrup. S.C. 1993. Human disturbances of denning polar bears in Alaska. Arctic 46(3):246-250.

Amstrup, S.C., and C. Gardner. 1994. Polar bear maternity denning in the Beaufort Sea. J. Wildl. Manage. 58(1):1-10.

Amstrup, S.C., I. Stirling, and J.W. Lentfer. 1986. Past and present status of polar bears in Alaska. Wildl. Soc. Bull. 14:241-254.

Amstrup, S.C., C. Gardner, K.C. Myers, and F.W. Oehme. 1989. Ethylene glycol (antifreeze) poisoning in a free-ranging polar bear. Vet. Hum. Toxicol. 31(4):317-319.

Amstrup, S.C., G.M. Durner, and T.L. McDonald. 2000. Estimating Potential Effects of Hypothetical Oil Spills from the Liberty Oil Production Island on Polar Bears. Anchorage, AK: U. S. Geological Survey, Biological Resources Division. 42 pp.

Amstrup, S.C., T.L. McDonald, and I. Stirling. 2001. Polar bears in the Beaufort Sea: A 30-year mark-recapture history. J. Agric. Biol. Environ. Stat. 6(2):221-234.

Amstutz, D.E., and W.B. Samuels. 1984. Offshore oil spills: Analysis of risks. Mar. Environ. Res. 13(4):303-319.

Anadarko Petroleum Corporation. 2002. Anadarko Petroleum Corporation's Arctic Platform: Press Release, 2pp.

Anderson, B.A., and S.M. Murphy. 1988. Lisburne Terrestrial Monitoring Program 1986 and 1987: The Effects of the Lisburne Powerline on Birds. Final Report. Fairbanks, AK: Alaska Biological Research.

Anderson, B.A., R.J. Ritchie, A.A. Stickney, and A.M. Wildman. 2000. Avian Studies in the Kuparuk Oilfield, Alaska, 1999. Fairbanks, AK: ABR.

Anderson, B.A., R.J. Ritchie, A.A. Stickney, and A.M. Wildman. 2001. Avian Studies in the Kuparuk Oilfield, Alaska, 2000. Unpublished report. ABR, Inc., Fairbanks, AK.

Andersen, D.E., O.J. Rongstad, and W.R. Mytton. 1990. Home-range changes in raptors exposed to increased human activity levels in southeastern Colorado. Wildl. Soc. Bull. 18(2):134-142.

Ankney, C.D. 1982. Annual cycle of body weight in lesser snow geese. Wildl. Soc. Bull. 10(1):60-64.

AOGA (Alaska Oil and Gas Association). 2001. Alaska's North Slope Oilfields. Technical Briefs. Alaska Oil and Gas Association, Anchorage, AK. June 2001. 120pp.

AOGCC (Alaska Oil and Gas Conservation Commission). 1998. 1998 Annual Report. State of Alaska, Alaska Oil and Gas Conservation Commission. 261 pp.

API (American Petroleum Institute). 1985. Oil Spill Response: Options for Minimizing Adverse Ecological Impacts. Publ. No. 4398. Washington, DC: American Petroleum Institute.

API (American Petroleum Institute). 1987. Waste Analysis Report. API Study for Regulation Determination. Washington, DC: American Petroleum Institute.

API (American Petroleum Institute). 1996. Characterization of Exploration and Production Associated Wastes. Publ. No. DR53. Washington, DC: American Petroleum Institute.

ARCO (ARCO Alaska, Inc.). 1984. Press Release: Prudhoe Bay Waterflood Project. June 14, 1984. Public Affairs Division, ARCO Alaska, Inc., Anchorage, AK.

ARCO/ BP/ Exxon (ARCO Alaska, Inc., BP Exploration Alaska, and Exxon). 1997. Prudhoe Bay Unit. DS-4 Surface Broach – March 17-21, 1997. Incident Report. Prepared by Investigation Team: ARCO Alaska, Inc., BP Exploration Alaska and Exxon, for Alaska Oil and Gas Conservation Commission. 37 pp.

Arft, A.M., M.D. Walker, J. Gurevitch, J.M. Alatalo, M.S. Bret-Harte, M. Dale, M. Diemer, F. Gugerli, G.H.R. Henry, M.H. Jones, R.D. Hollister, I.S. Jonsdottir, K. Laine, E. Levesque, G.M. Marion, U. Molau, P. Molgaard, U. Nordenhall, V. Raszhivin, C.H. Robinson, G. Starr, A. Stenstrom, M. Stenstrom, O. Totland, P.L. Turner, L.J. Walker, P.J. Webber, J.M. Welker, and P.A. Wookey. 1999. Response of tundra plants to experimental warming: A meta-analysis of the Internation Tundra Experiment. Ecol. Monogr. 69(4):491-512.

Arrow, K.J., and A.C. Fisher. 1974. Environmental preservation, uncertainty, and irreversibility. Quart. J. Econ. 88(2):312-319.

ASRC (Arctic Slope Regional Corporation). 2001. The ASRC 2000 Annual Report. Arctic Slope Regional Corporation, Barrow, AK [Online]. Available: http://www.asrc.com/page24.html [accessed Dec. 11, 2002].

Auerbach, N.A., M.D. Walker, and D.A. Walker. 1997. Effects of roadside disturbance on substrate and vegetation properties in arctic tundra. Ecol. Appl. 7(1):218-235.

Baker, M. 1985. Two Year Study of the Effects of a Winter Brine Spill on Tussock Tundra. Final report. Prepared for ARCO Alaska Inc., Anchorage, AK.

Baker, M., Jr. 2000. Colville River Pipeline Crossing. HDD Crossing Design, Alpine Development Project. Michael Baker, Jr., Inc, Anchorage, AK [Online]. Available: http://www.mbakercorp.com/ [accessed October 23, 2002].

Ballard, W.B., M.A. Cronin, and H.A. Whitlaw. 2000. Caribou and oil fields. Pp. 85-104 in The Natural History of An Arctic Oil Field, J.C. Truett, and S.R. Johnson, eds. San Diego: Academic Press.

Banet Jr., A.C. 1991. Oil and Gas Development on Alaska's North Slope: Past Results and Future Prospects. Open File Report 34. Anchorage, AK: Bureau of Land Management, Alaska State Office. 42 pp.

Banko, W.E., and R.H. Mackay. 1964. Our native swans. Pp. 155-164 in Waterfowl Tomorrow, J.P. Linduska, ed. Washington, DC: U.S. Dept. of Interior, Bureau of Sport Fisheries and Wildlife, Fish and Wildlife Service.

Barnes, P.W., and E. Reimnitz. 1974. Sedimentary processes on arctic shelves off the northern coast of Alaska. Pp. 439-476 in The Coast and Shelf of the Beaufort Sea: Proceedings of a Symposium on Beaufort Sea Coast and Shelf Research, J.C. Reed and J.E. Sater, eds. Arlington, VA: Arctic Institute of North America.

Barnes, P.W., D.M. Rearic, and E. Reimnitz. 1984. Ice gouging characteristics and processes. Pp. 155-212 in The Alaskan Beaufort Sea: Ecosystems and Environments, P.W. Barnes, D.M. Schell, and E. Reimnitz, eds. Orlando: Academic Press.

Barry, T.W. 1967. Geese of the Anderson River Delta, Northwest Territories. Ph.D. Thesis. University of Alberta, Edmonton.

Bates, E.V. 1978. The impact of energy boom-town growth on rural areas. Social Casework 59:73-82.

Batzli, G.O., R.G. White, S.F. MacLean, Jr., F.A. Pitelka, and B.D. Collier. 1980. The herbivore-based trophic system. Pp. 335-410 in An Arctic Ecosystem: The Coastal Tundra at Barrow, Alaska, J. Brown, P.C. Miller, L.L. Tieszen, and F.L. Bunnell, eds. Stroudsburg, PA: Dowden, Hutchinson and Ross, Inc.

BEA (U.S. Bureau of Economic Analysis). 2002. Local Area Personal Income. Regional Accounts Data, Regional Economic Information System. Bureau of Economic Analysis, U.S. Department of Commerce [Online]. Available: http://www.bea.doc.gov/bea/regional/reis/ [accessed Dec. 11, 2002].

Bellrose, F.C. 1980. Ducks, Geese and Swans of North America, 3rd Ed. Harrisburg, PA: Stackpole Books.

Bendock, T.N. 1976. De-watering Effects of Industrial Development on Arctic Fish Stocks. Prepared for Alaska Board of Fisheries. ADF&G, Div. Sport Fish, Fairbanks, AK. 13pp. (as cited in Winters et al. 1988).

Bendock, T.N. 1979. Beaufort Sea estuarine fishery study. Pp. 670-729 in Environmental Assessment of the Alaskan Continental Shelf, Final Reports of the Principal Investigators, Vol. 4. U.S. Bureau of Land Management and National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Boulder, CO.

Bendock, T.N., and J.M. Burr. 1986. Arctic Area Trout Studies, T-7-1, Vol. 27. 1 July 1985-30 June 1986, Federal Aid in Fish Restoration F-10-1 and Anadromous Fish Studies, Sport Fish Investigations of Alaska. Juneau, AK: Alaska Department of Fish and Game, Sport Fish Division. 75pp.

Bergerud, A.T. 1975. The reproductive season of Newfoundland caribou. Can. J. Zool. 53(9):1213-1221.

Bergerud, A.T. 1979. A review of the population dynamics of caribou and wild reindeer in North America. Pp. 556-581 in Proceedings of the Second International Reindeer/Caribou Symposium, Sept. 17-21, 1979, Roros, Norway, Part B, E. Reimers, E. Gaare, and S. Skjenneberg, eds. Trondheim: Direktoratet for vilt og ferskvannsfisk.

Bergerud, A.T., and R.E. Page. 1987. Displacement and dispersion of parturient caribou at calving as antipredator tactics. Can. J. Zool. 65:1597-1606.

Bergman, R.D., R.L. Howard, K.F. Abraham, and M.W. Weller. 1977. Waterbirds and Their Wetland Resources in Relation to Oil Development at Storkersen Point, Alaska. U.S. Fish Wildl. Serv. Resour. Publ. 129. Washington, DC: U.S. Dept. of the Interior, Fish and Wildlife Service. 38pp.

Bergstein, P.E., and J.R. Vestal. 1978. Crude oil biodegradation in arctic tundra ponds. Arctic 31(3):158-169.

Berry, M.C. 1975. The Alaska Pipeline: The Politics of Oil and Native Land Claims. Bloomington: Indiana University Press.

Bettelheim, B. 1943. Individual and mass behavior in extreme situations. Journal of Abnormal and Social Psychology 38:417-452.

Bill, M. 2000. Prudhoe Bay Unit Grind and Inject Project, Surfcote Pad Injection: Area Injection Order No. 4C, Rule 10, Third Annual Performance Report, July 1, 2000. Phillips Alaska, Inc., Anchorage, AK, to Alaska Oil and Gas Conservation Commission, Anchorage, AK. 3pp.

Binford, L.R. 1978. Nunamiut Ethnoarchaeology. New York: Academic Press.

Binford, L.F. 2002. In Persuit of the Past, Decoding the Archaeological Record With a New Afterword. Berceley, CA: University of California Press.

Bird, K.J. 1998. Assessment overview. Chapter AO in The Oil and Gas Resource Potential of the Arctic National Wildlife Refuge 1002 Area, Alaska, Open File Report 98-34. Menlo Park: U.S. Geological Survey, U.S. Dept. of the Interior [Online]. Available: http://energy.cr.usgs.gov/OF98-34/AO.pdf [accessed Dec. 11, 2002].

Bird, K.J., and D.W. Houseknecht. 1998. Arctic National Wildlife Refuge, 1002 Area, Petroleum Assessment, 1998. USGS Fact Sheet FS-040-98. Reston, VA: U.S. Geological Survey.

Bird, K.J., and D.W. Houseknecht. 2002. U.S. Geological Survey 2002 Petroleum Resource Assessment of the National Petroleum Reserve in Alaska (NPRA). USGS Fact Sheet 045-02. Menlo Park: U.S. Geological Survey, U.S. Dept. of the Interior [Online]. Available: http://geopubs.wr.usgs.gov/fact-sheet/fs045-02/ [accessed Dec. 11, 2002]

Bird, K.J., and L.B. Magoon. 1987. Petroleum Geology of the Northern Part of the Arctic National Wildlife Refuge, Northeastern Alaska. U.S. Geological Survey Bulletin 1778. Washington: U.S. Dept. of the Interior, U.S. Geological Survey.

Bishop, S.C., and R.D. Cameron. 1990. Habitat use by post-parturient female caribou of the central arctic herd. Pp. 9 in Impacts of Development on Wildlife in Alaska Abstracts, Alaska Chapter, Annual Meeting of The Wildlife Society, April 4-6, 1990, Juneau, AK.

Bliss, L.C., and R.W. Wein. 1972. Plant community responses to disturbances in the western Canadian Arctic. Can. J. Bot. 50:1097-1109.

BLM (Bureau of Land Management). 1982. Proposed Outer Continental Shelf Oil and Gas Lease Sale 71 Diapir Field. Final Environmental Impact Statement. BLM-YK-ES-81-010-1792. Alaska Outer Continental Shelf Office, Anchorage, AK.

BLM (Bureau of Land Management). 1990. National Petroleum Reserve-Alaska. Lease History Summary. Bureau of Land Management. 6 pp.

BLM (Bureau of Land Management). 1998. The Brooks Mountain Range. Coldfoot Interagency Visitor Center. Bureau of Land Management, BLM Northern Field Office [Online]. Available: http://wwwndo.ak.blm.gov/arcticinfo/topics/brooks.htm. [accessed Dec. 11, 2002].

BLM (Bureau of Land Management). 2001. North Slope Sales Summary Maps, with Emphasis on NPR-A: Minerals Management Service, 4 sheets.

BLM/MMS (Bureau of Land Management/ Minerals Management Service). 1998. Northeast National Petroleum Reserve-Alaska. Final Integrated Activity Plan/ Environmental Impact Statement. Vols 1 and 2. Prepared by U.S. Dept. of the Interior, Bureau of Land

Management and Minerals Management Service, Anchorage, AK. Washington, DC: U.S. Government Printing Office.

Bockstoce, J. 1978. History of commercial whaling in Arctic Alaska. Alaska Geographic 5(4):17-26.

Bockstoce, J.R., ed. 1988. The Journal of Rochfort Maguire, 1852-1854: Two Years at Point Barrow, Alaska, Aboard HMS Plover in the Search for Sir John Franklin. London: Hakluyt Society.

Boesch, D.F., and N.N. Rabalais, eds. 1987. Long-Term Environmental Effects of Offshore Oil and Gas Development. New York: Elsevier Applied Science.

Bowman, T.D., R.A. Stehn, and K.T. Scribner. 1997. Glaucous Gull Predation of Goslings on the Yukon-Kuskokwim Delta, Alaska. Migratory Bird Management, U. S. Fish and Wildlife Service, Anchorage, AK.

BP Exploration. 1991. Industry-Sponsored Research on Alaska's North Slope. Environmental and Regulatory Affairs, BP Explorations (Alaska), Inc., Anchorage, AK.

BP Exploration. 1992. NORM – Naturally Occurring Radioactive Material: What Is It and How Is BP Exploration Responding? BP Exploration (Alaska), Inc., Anchorage, AK. 16 pp.

BP Exploration. 1998a. Environmental Performance on Alaska's North Slope. BP Exploration (Alaska), Inc., Anchorage, AK. February.

BP Exploration. 1998b. BP Exploration in Alaska 1998. BP Exploration (Alaska), Inc., Anchorage, AK.

BP Exploration. 1998c. Spill prevention and response. Pp. 3-53- to 3-61 in Environmental Environmental Performance on Alaska's North Slope. BP Exploration (Alaska), Inc., Anchorage, AK. February.

BP Exploration. 2001a. Alternative Well Cellar Evaluation. Amendment of the ARCO Alaska, Inc. Prudhoe Bay Unit and Greater Point McIntyre Area Oil Discharge and Prevention Contingency Plan, No. 984-CP-4138 for Northwest Eileen Development Operations, Anchorage, AK. In Appendix G, BP Exploration (Alaska), Inc. 2002. Oil Discharge Prevention and Contingency Plan, Greater Prudhoe Bay, North Slope, Alaska. ADEC Plan No. 014-CP-5079.

BP Exploration. 2001b. BP Statistical Review of World Energy 2001. [Online]. Available: http://www.bp.com/centres/energy/world_stat_rev/oil/prices-2.asp [accessed November 27, 2001].

BP Exploration/ARCO. 1993. North Slope Waste Management: Minimization, Recycling, Disposal. BP Exploration (Alaska), Inc., and ARCO Alaska, Inc., Anchorage, AK.

BP Exploration/ARCO. 1997. Arctic Oil: Energy for Today and Tomorrow, BP Exploration (Alaska), Inc., and ARCO Alaska, Inc., Anchorage, AK.

BP Northstar. 2002. BP in Alaska: Northstar Information. Exploring Alaska Northstar. Facts Sheets. Overview [Online]. Available: http://alaska.bp.com/alaska/northstar/factsheets/page11_summary.htm [accessed Dec. 11, 2002].

Bradshaw, C.J.A., S. Boutin, and D.M. Hebert. 1998. Energetic implications of disturbance caused by petroleum exploration to woodland caribou. Can. J. Zool. 76(7):1319-1324.

Braham, H.W., M.A. Fraker, and B.D. Krogman. 1980. Spring migration of the western arctic population of bowhead whales. Mar. Fish. Rev. 42(9-10):36-46.

Braithwaite, L. 1980. Baleen plate fouling (RU 679a). Pp. 471-492 in Investigation of the Occurrence and Behavior Patterns of Whales in the Vicinity of the Beaufort Sea Lease Area. Final Report for the period October 1, 1978 through November 30, 1979. Naval Arctic Research Laboratory, Barrow, AK. 753 pp.

Braithwaite, L.F., M.G. Aley, and D.L. Slater. 1983. The Effects of Oil on the Feeding Mechanism of the Bowhead Whale. AA851-CTO-55. Prepared for the Department of the Interior, from Brigham Young University, Provo, UT. 45 pp.

Breiwick, J.M., E.D. Mitchell, and D.G. Chapman. 1981. Estimated initial population size of the Bering Sea stock of bowhead whale, *Balaena mysticetus*: An interactive method. Fish. Bull. 78(4):843-853.

Brewer, K., M. Gallagher, P. Regos, P. Isert, and J. Hall. 1993. Kuvlum #1 Exploration Prospect: Site Specific Monitoring Program. Final Report. Prepared by Coastal and Offshore Pacific Corporation, Walnut Creek, CA, for ARCO Alaska, Inc., Anchorage, AK. 80pp.

Brewer, M.C. 1958a. Some results of geothermal investigations of permafrost in northern Alaska, Trans. Am Geophys. Union 39(1). Menlo Park CA: U.S. Geological Survey.

Brewer, M.C. 1958b. The Thermal Regime of an Arctic Lake. Trans. Am. Geophys. Union 39(2). Menlo Park, CA: U.S. Geological Survey.

Britton, M.E. 1967. Vegetation of the arctic tundra. Pp. 67-130 in Arctic Biology, P. Hansen, ed. Corvallis: Oregon State University Press.

Brooks, A.H. 1909. Petroleum. Pp. 61-62 in The Mining Industry in 1908. U.S. Geological Survey Bulletin 379. Washington, DC: Government Printing Office.

Brooks, S.B., T.L. Crawford, and W.C. Oechel. 1997. Measurement of carbon dioxide emissions plumes from Prudhoe Bay, Alaska oil fields. J. Atmos. Chem. 27(2): 197-207.

Brower, C.D. 1942. Fifty Years Below Zero: A Lifetime of Adventure in the Far North. London: R. Hale.

Brower Jr., H.K., and R.T. Hepa. 1998. North Slope Borough Subsistance Harvest Documentation Project: Data for Nuiqsut, Alaska for the Period July 1, 1994, to June 30, 1995. North Slope Borough, Department of Wildlife Management, Borrow, AK. 45pp.

Brower Jr., H.K., and R.T. Opie. 1996. North Slope Borough Subsistence Harvest Documentation Project: Data for Anaktuvuk Pass, Alaska for the Period July 1, 1994 to June 30, 1995. North Slope Borough, Department of Wildlife Management, Barrow, AK.

Brower Jr., H.K., and R.T. Opie. 1997. North Slope Borough Subsistence Harvest Documentation Project: Data for Anaktuvuk Pass, Alaska for the Period July 1, 1994 to June 30, 1995. North Slope Borough, Department of Wildlife Management, Barrow, AK.

Brown, J., and R.L. Berg, eds. 1980. Environmental Engineering and Ecological Baseline Investigations Along the Yukon-Prudhoe Bay Haul Road. CRREL 80-19. Prepared for U.S. Dept. of Transportation, Federal Highway Administration, Office of Reseach and Development, Environmental Division, by U.S. Army Cold Regions Research and Engineering Laboratory, Corps of Engineers, Hanover, NH.

Buist, I.A., S.G. Potter, and D.F. Dickens. 1983. Fate and behavior of water-in-oil emulsions in ice. Pp. 263-279 in Proceedings of the Sixth Arctic Marine Oilspill Program Technical Seminar. Ottawa: Environment Canada.

Burch Jr., E.S. 1976. The "Nunamiut " concept and the standardization of error. Pp. 52-92 in Contributions to Anthropology: The Interior Peoples of Northern Alaska, E.S. Hall, ed. Archaeological Survey of Canada No. 49. Ottawa: National Museums of Canada.

Burdge, R.J. 1994. A Conceptual Approach to Social Impact Assessment. Middleton, WI: Social Ecology Press.

Burgess, R.M. 2000. Arctic fox. Pp. 159-178 in The Natural History of An Arctic Oil Field, J.C. Truett, and S.R. Johnson, eds. San Diego: Academic Press.

Burgess, R.M., J.R. Rose, P.W. Banyas, and B.E. Lawhead. 1993. Arctic Fox Studies in the Prudhoe Bay Unit and Adjacent Undeveloped Areas, 1992. Prepared by Alaska Biological Research, Inc., Fairbanks, AK, for BP Exploration (Alaska) Inc., Anchorage, AK.

Busdosh, M., C.L. Beehler, G.A. Robilliard, and K.R. Tarbox. 1985. Distribution and abundance of kelp in the Alaskan Beaufort Sea near Prudhoe Bay. Arctic 38(1):18-22.

Cameron, R.D. 1994. Reproductive pauses by female caribou. J. Mammal. 75:10-13.

Cameron, R.D. 1995. Can petroleum development depress the productivity of arctic caribou? Pp. 36 in Book of Abstracts, the 2nd International Arctic Ungulate Conference, August 13-17, 1995, Fairbanks, AK.

Cameron, R.D., and J.M. Ver Hoef. 1994. Predicting parturition rate of caribou from autumn body mass. J. Wildl. Manage. 58(4):674-679.

Cameron, R.D., and R.G. White. 1992. Importance of summer weight gain to the reproductive success of caribou in arctic Alaska. Rangifer Special Issue 9:397.

Cameron, R.D., and K.R. Whitten. 1979a. Seasonal movements and sexual segregation of caribou determined by aerial survey. J. Wildl. Manage. 43:626-633.

Cameron, R.D., and K.R. Whitten. 1979b. Influence of the Trans-Alaska Pipeline corridor on the local distribution of caribou. Pp. 475-484 in Proceedings of the Second International Reindeer/Caribou Symposium, Sept. 17-21, 1979, Roros, Norway, Part B, E. Reimers, E. Gaare, and S. Skjenneberg, eds. Trondheim: Direktoratet for vilt og ferskvannsfisk.

Cameron, R.D., K.R. Whitten, W.T. Smith, and D.D. Roby. 1979. Caribou distribution and group composition associated with construction of the Trans- Alaska Pipeline. Can. Field-Nat. 93:155-162.

Cameron, R.D., D.J. Reed, J.R. Dau, and W.T. Smith. 1992. Redistribution of calving caribou in response to oil field development on the Arctic Slope of Alaska. Arctic 45(4):338-342.

Cameron, R.D., W.T. Smith, S.G. Fancy, K.L. Gerhart, and R.G. White. 1993. Calving success of female caribou in relation to body weight. Can. J. Zool. 71(3):480-486.

Cameron, R.D., E.A. Lenart, D.J. Reed, K.R. Whitten, and W.T. Smith. 1995. Abundance and movements of caribou in the oilfield complex near Prudhoe Bay, Alaska. Rangifer 15(1):3-7.

Cameron, R.D., D.E. Russell, K.L. Gerhart, R.G. White, and J.M. Ver Hoef. 2000. A model for predicting the parturition status of arctic caribou. Pp. 139-141 in Proceedings of the 8th North American Caribou Workshop, Whitehorse, Yukon, Canada, April 20-24, 1998, R. Farnell, D. Russell, and D. van de Wetering, eds. Rangifer Spec. Issue 12. Tromso, Norway: Nordic Council for Reindeer Research.

Cameron, R.D., W.T. Smith, R.G. White, and B. Griffith. 2002. The central arctic caribou herd. Part 1. Section 4 in Arctic Refuge Coastal Plain Terrestrial Wildlife Research Summaries, D.C. Douglas, and P.E. Reynolds, eds. Biological Science Report USGS/BRD/BSR-2002-0001. U.S. Geological Survey, Biological Resources Division [Online]. Available: http://alaska.usgs.gov/BSR-2002/usgs-brd-bsr-2002-001.html [accessed Dec. 11, 2002].

Cannon, T.C., B.A. Adams, D. Glass, and T. Nelson. 1987. Fish distribution and abundance. Pp. 1-38 in 1985 Final Report for the Endicott Environmental Monitoring Program, Vol. 6. Prepared by Envirosphere Company, Anchorage, AK, for U.S. Dept. of the Army, Alaska District, Corps of Engineers.

Cantlon, J.E. 1961. Plant Cover in Relation to Macro-, Meso- and Micro-Relief. Final Report. Grants ONR-208 and 216. Office of Naval Research, Arctic Institute of North America, University of Calgary, Calgary, Alberta.

Carey, A.G. 1978. The distribution, abundance, diversity and productivity of the western Beaufort Sea benthos. Pp. 127-252 in Environmental Assessment of the Alaskan Continental Shelf, Annual Report of Principal Investigators, Vol. 4. U.S. Bureau of Land Managemet and National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Boulder, CO.

Carroll, G. 1995. Game Management Unit 26A brown bear management report. Pp. 289-303 in Brown Bear, Management Report of Survey-Inventory Activities, 1 July 1992-30 June 1994, M.V. Hicks, ed. Federal Aid in Wildlife Restoration Proj. W-24-1 and W-24-2. Juneau, AK: Alaska Dept. of Fish and Game, Division of Wildlife Conservation.

Carroll, G. 1999. Brown bear. Survey-inventory management report, Unit 26A. Pp. 295-306 in Brown Bear. Federal Aid in Wildlife Restoration Management Report: Survey-Activities, 1 July 1996- 30 June 1998, Grants W-24-5 and W-27-1, Study 4.0, M.V. Hicks, ed. Juneau, AK: Alaska Dept. of Fish and Game, Division of Wildlife Conservation.

Carroll, G.M., J.C. George, L.F. Lowry, and K.O. Coyle. 1987. Bowhead whale, *Balaena mysticetus*, feeding near Point Barrow, Alaska during the 1985 spring migration. Arctic 40(2):105-110.

Carson, C.E., and K.M. Hussey. 1959. The multiple-working hypothesis as applied to Alaska's oriented lakes. Proc. Iowa Acad. Sci. 66:334-349.

Carson, R.T., R.C. Mitchell, W.M. Hanemann, R.J. Kopp, S. Presser, and P.A. Ruud. 1992. A Contingent Valuation Study of Lost Passive Use Values Resulting from the Exxon Valdez Oil Spill: Report to the Attorney General of the State of Alaska. Juneau, AK: State of Alaska Attorney General's Office.

Cater, T.C., L.J. Rossow, and M.T. Jorgenson. 1999. Long-Term Ecological Monitoring of Tundra Affected by a Crude Oil Spill Near Drill Site 2U, Kuparuk Oilfield, Alaska, 1989-1996. 1996 Annual Report. Prepared for ARCO Alaska, Inc, and Kuparuk River Unit, by Environmental Research & Services, ABR, Inc., Fairbanks, AK.

Cederquist, S.C. 2000. Cutting edge technology Alpine project brings technology "firsts" to Alaska's North Slope. Pipeline and Gas Journal, May 2000 [Online]. Available: http://www.undergroundinfo.com/pgj%20archive/archie93.htm [accessed May 6, 2002].

Chance, N.A. 1966. The Eskimo of North Alaska. New York: Holt, Rinehart and Winston.

Chan-McLeod, A.C.A., R.G. White, and D.F. Holleman. 1994. Effects of protein and energy intake, body condition, and season on nutrient partitioning and milk production in caribou and reindeer. Can. J. Zool. 72(5):938-947.

Chan-McLeod, A.C.A., R.G. White, and D.E. Russell. 1999. Comparative body composition strategies of breeding and non-breeding female caribou. Can. J. Zool. 77(12):1901-1907.

Chapin, D.M., and C.S. Bledsoe. 1992. Nitrogen fixation in arctic plant communities. Pp. 301-319 in Arctic Ecosystems in a Changing Climate: An Ecophysiological Perspective, F.S.

Chapin, III, R.L. Jefferies, J.F. Reynolds, G.R. Shaver, J. Svoboda, and E.W. Chu, eds. San Diego: Academic Press.

Chapin, F.S. III, and M.C. Chapin. 1980. Revegetation of an arctic disturbed site by native tundra species. J. Appl. Ecol. 17(2):449-456.

Chapin, F.S. III, and G.R. Shaver. 1981. Changes in soil properties and vegetation following disturbance of Alaskan arctic tundra. J. Appl. Ecol. 18(2):605-617.

Chapin, F.S. III, and G.R. Shaver. 1985. Individualistic growth response of tundra plant species to manipulation in the field. Ecology 66(2):564-576.

Chapin, F.S. III, and G.R. Shaver. 1988. Differences in carbon and nutrient fractions among arctic growth forms. Oecologia 77(4):506-514.

Chapin, F.S. III, D.A. Johnson, and J.D. McKendrick. 1980. Seasonal movements of nutrients in plants of differing growth forms in an Alaskan tundra ecosystem: Implications for herbivory. Ecology 68(1):189-210.

Chapin, F.S. III, G.R. Shaver, and R.A. Kedrowski. 1986. Environmental control over carbon, nitrogen, and phosphorus chemical fractions in Eriophorum vaginatum L. in Alaskan tussock tundra. J. Ecol. 74(1):167-195.

Chapman, W.L., and J.E. Walsh. 1993. Recent variation of sea ice and air temperature in high latitudes. Bull. Am. Meteorol. Soc. 74(1):33-47.

Chernov, Y.I. 1995. Diversity of the Arctic terrestrial fauna. Pp. 81-95 in Arctic and Alpine Biodiversity: Patterns, Causes and Ecosystem Consequences, F.S. Chapin III, and C. Körner, eds. New York: Springer-Verlag.

Child, K.N. 1973. A Study of the Reactions of Barren-Ground Caribou *(Rangifer tarandus granti)* to Simulated Pipelines and Associated Structures at Prudhoe Bay, Alaska. Completion Report to Alyeska Pipeline Service Company, BP Alaska, Inc., and U.S. Bureau of Sport, Fisheries and Wildlife, by Alaska Cooperative Wildlife Research Unit, University of Alaska, Fairbanks.

Child, K.N. 1974. Reaction of caribou to various types of simulated pipelines at Prudhoe Bay, Alaska. Pp. 805-812 in The Behaviour of Ungulates and Its Relation to Management, V. Geist, and F.R. Walther, eds. IUCN No. 24. Morges, Switzerland: International Union for Conservation of Nature and Natural Resources.

Clark, C.W., and W.T. Ellison. 1988. Numbers and Distributions of Bowhead Whales, *Balaena mysticetus*, Based on the 1985 Acoustic Study off Pt Barrow, Alaska. Report of International Whaling Commission 38:365-370.

Clark, C.W., and W.T. Ellison. 1989. Numbers and Distributions of Bowhead Whales, *Balaena mysticetus*, Based on the 1986 Acoustic Study off Pt Barrow, Alaska. Report of International Whaling Commission 39:297-303.

Clark, C.W., W. Ellison, and K. Beeman. 1985. Acoustic Tracking and Distribution of Migrating Bowhead Whales, *Balaena mysticetus*, off Point Barrow, Alaska in the Spring of 1984. Submitted as paper SC/37/PS11 for the Scientific Committee of the International Whaling Commission, June 1985.

Clark, C.W., R. Charif, S. Mitchell, and J. Colby. 1996. Distribution and Behavior of the Bowhead Whale, *Balaena mysticetus*, Based on Analysis of Acoustic Data Collected During the 1993 Spring Migration off Point Barrow, Alaska. Report of the International Whaling Commission 46:541-552.

Clough, J.G., C.E. Barker, and A.D. Scott. 2000. Alaska methane remains untapped, new state program may spark progress. AAPG Explorer (August):54-55.

Clough, N.K., A.C. Christiansen, and P.C. Patton, eds. 1987. Arctic National Wildlife Refuge, Alaska, Coastal Plain Resource Assessment. Washington, DC: U.S. Dept. of the Interior.

Clow, G.D. 1992. The extant of temporal smearing in surface-temperature profiles: Some problems and methods. Paleogeogr. Palaeoclim. Palaeoecol. 98(2/4):81-86.

Clow, G.D., and F.E. Urban. 2002. Large Permafrost Warming in Northern Alaska During the 1990's Determined from GTN-P Borehole Temperature. Eos Trans. AGU 83(47) Fall Meet. Suppl. Abstract B11E-04. [Online]. Available: http://www.agu.org/meetings/fm02/ [accessed Jan.8, 2003].

Clymo, R.S., and P.M. Hayward. 1982. The ecology of Sphagnum. Pp. 229-289 in Bryophyte Ecology, J.E. Smith, ed. London: Chapman & Hall.

Coastal Frontiers Corporation and LGL Ecological Research Associates, Inc. 1998. Liberty Development 1997-98 Boulder Patch Survey. Final Report. Prepared for BP Exploration (Alaska) Inc., Anchorage, AK. 46pp. + appendices.

Coates, P.A. 1991. The Trans-Alaska Pipeline Controversy: Technology, Conservation, and the Frontier. Bethlehem: Lehigh University Press.

Cody, M.L. 1985. Habitat Selection in Birds. Orlando: Academic Press.

Collett, T.S. 1995. Gas hydrate resources of the United States. In 1995 National Assessment of the U.S. Oil and Gas Resources, Results, Methods, and Supporting Data, D.L. Gautier, G.L. Dolton, K.I. Takahashi, and K.L. Varnes, eds. USGS DDS 30. (CD-ROM). Reston, VA: U.S. Geological Survey [Online]. Available: http://energy.cr.usgs.gov/1995OGData/Hydrates/HYDRATE.pdf [accessed Dec. 2, 2002].

Collett, T.S., K.J. Bird, K.A. Kvenvolden, and L.B. Magoon. 1988. Geologic Interrelations Relative to Gas Hydrates within the North Slope of Alaska. U.S. Geological Survey Open-File Report 88-389. Denver, CO: U.S. Dept. of Interior, Geological Survey.

Colonell, J.M., and B.J. Gallaway. 1997. Wind-driven transport and dispersion of age-0 arctic ciscoes along the Alaskan Beaufort coast. Pp. 90-103 in Fish Ecology in Arctic North America, J.B. Reynolds, ed. American Fisheries Society Symposium 19. Bethesda, MD: American Fisheries Society.

Colonell, J.M., and A.W. Niedoroda. 1990. Appendix B. Coastal oceanography of the Alaskan Beaufort Sea. Pp. B-1 to B-74 in An Assessment of Marine Environmental Impacts of West Dock Causeway, J.M. Colonell, and B.J. Gallaway, eds. Prepared for the Prudhoe Bay Unit Owners and ARCO Alaska Inc., by LGL Alaska Research Associates, Inc., and Environmental Science and Engineering , Inc., Anchorage, AK. 132p+appendices.

Comfort, G., A. Dinovitzer, and R. Lazor. 2000. Independent Risk Assessment for the Liberty Pipeline. 5095C.FR. Prepared by Fleet Technology Limited, Kanata, Ontario, for Mineral Management Service, Anchorage, AK. September 2000. [Online]. Available: http://www.mms.gov/alaska/reports/libertyfeis/Documents/Fleet%20Independent%20Risk%20Evaluation.pdf [accessed Dec.11, 2002].

Cominco. 1990. Red Dog Facts. Cominco Alaska. July 1990. 6 pp.

Conant, B., and D.J. Groves. 1997. Alaska-Yukon Waterfowl Breeding Population Survey May 15 to June 14, 1997. U.S. Fish and Wildlife Service, Juneau, AK. 29pp.

Conant, B., J.I. Hodges, and D.J. Groves. 2000. Alaska-Yukon Waterfowl Breeding Population Survey, May 15 to June 10, 2000. U.S. Fish and Wildlife Service, Juneau, AK. 32pp.

Connors, P.G., and R.W. Risebrough. 1979. Shorebird dependence on arctic littoral habitats. Pp. 271-329 in Environmental Assessment of the Alaskan Continental Shelf, Annual Report 1. U.S. Bureau of Land Managemet and National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Boulder, CO.

Conwell, C.N., and D.M. Triplehorn. 1976. High-quality coal near Point Hope, northwestern Alaska. Pp. 31-35 in Short Notes on Alaskan Geology, 1976. Geological Report 51. College, AK: Alaska Division of Geological and Geophysical Surveys.

Cooke, F., R.F. Rockwell, and D.B. Lank. 1995. The Snow Geese of La Pérouse Bay Natural Selection in the Wild. Oxford: Oxford University Press.

Cooney, R.T. 1988. Arctic plankton communities. Pp. 163-168 in Alaska OCS Region 1987 Arctic Information Transfer Meeting Conference, Conference proceedings, November 17-20, 1987, Anchorage, AK. MMS88-0040. Prepared for Minerals Management Service, Alaska OCS Region, Anchorage, AK, by MBC Applied Environmental Sciences, Costa Mesa. June 1988.

Cortese, C.F., and B. Jones. 1977. The sociological analysis of boom towns. West. Sociol. Rev. 8:76-90.

Cotter, P.A., and B.A. Andres. 2000. Nest density of shorebirds inland from the Beaufort Sea coast, Alaska. Can. Field Nat. 114(2):287-291.

Cox, J.C., and L.A. Schultz. 1980. The transport and behaviour of spilled oil under ice. Pp. 45-61 in Proceedings of the Third Arctic Marine Oilspill Program Technical Seminar, June 3-5, 1980, Edmonton, Alberta. Ottawa: Research and Development Division, Environmental Emergency Branch, Environmental Protection Service.

Craig, P.C. 1984. Fish use of coastal waters of the Beaufort Sea: A review. Trans. Am. Fish. Soc. 113(3):265-282.

Craig, P.C. 1987. Subsistence Fisheries at Coastal Villages in the Alaskan Arctic, 1970-1986. Alaska OCS Socioeconomic Studies Program, Technical Report No. 129. Anchorage, AK: Minerals Management Service. 63pp.

Craig, P.C. 1989. An introduction to anadromous fishes in the Alaskan arctic. Pp. 27-54 in Research Advances on Anadromous Fish in Arctic Alaska and Canada, D.W. Norton, ed. Biological Papers of the University of Alaska 24. Fairbanks: Institute of Arctic Biology, University of Alaska.

Craig, P.C., and L. Haldorson. 1981. Part 4. Fish. Pp. 384-678 in Environmental Assessment of the Alaskan Continental Shelf, Final Reports of Principal Investigators, Vol. 7. Biological Studies. Office of Marine Pollution Assessment, National Oceanic & Atmospheric Administration, U.S. Dept. of Commerce and Bureau of Land Management, U.S. Dept. of Interior. February 1981.

Craig, P.C., and L. Haldorson. 1986. Pacific salmon in the North American Arctic. Arctic 39(1):2-7.

Craig, P.C., and P. McCart. 1975. Classification of stream types in Beaufort Seas drainages between Prudhoe Bay, Alaska and the Mackenzie Delta, N.W.T. Arct. Alpine Res. 7:183-198.

Craig, P.C., W.B. Griffiths, S.R. Johnson, and D.M. Schell. 1984. Trophic dynamics in an arctic lagoon. Pp. 347-380 in The Alaskan Beaufort Sea: Ecosystems and Environments, P.W. Barnes, D.M. Schell, and E. Reimnitz, eds. Orlando: Academic Press.

Crete, M., and J. Huot. 1993. Regulation of a large herd of migratory caribou: Summer nutrition affects calf growth and body reserves of dams. Can. J. Zool. 71(11):2291-2296.

Cronin, M.A., W.B. Ballard, J. Truett, and R. Pollard, eds. 1994. Mitigation of the Effects of Oil Field Development and Transportation Corridors on Caribou. Final Report to Alaska Caribou Steering Committee, from LGL Alaska Research Associates, Inc., Anchorage.

Cronin, M.A., S.C. Amstrup, G.M. Durner, L.E. Noel, T.L. McDonald, and W.B. Ballard. 1998. Caribou distribution during the post-calving period in relation to infrastructure in the Prudhoe Bay oil field, Alaska. Arctic 51(2):85-93.

Cronin, M.A., H.A. Whitlaw, and W.B. Ballard. 2000. Northern Alaska oil fields and caribou. Wildl. Soc. Bull. 28(4):919-922.

Cummings, R.G., D.S. Brookshire, W.D. Schulze, R.C. Bishop, and K.J. Arrow. 1986. Valuing Environmental Goods: An Assessment of the Contingent Valuation Method. Totowa, NJ: Rowland & Allanheld.

Curatolo, J.A., and S.M. Murphy. 1986. The effects of pipelines, roads, and traffic on movements of caribou, Rangifer tarandus. Can. Field Nat. 100(2):218-224.

D.F. Dickins Associates Ltd.,Vaudrey and Associates Inc., and S.L. Ross Environmental Research Ltd. 2000. Oil spills in Ice, Discussion Paper: A Review of Spill Response, Ice Conditions, Oil Behavior, and Monitoring. Prepared for Alaska Clean Seas. December 2000.

Dames & Moore. 1985. Prudhoe Bay Unit Waterflood Project Marine Life Return System Monitoring Program: June 11, 1984 through June 15, 1985. Annual Report to ARCO Alaska, Inc., and the Prudhoe Bay Unit Owners. December 1985.

Dames & Moore. 1986. Prudhoe Bay Unit Waterflood Project Marine Life Return System Monitoring Program: June 11, 1984 through September 22, 1985. Final Report to ARCO Alaska, Inc., and the Prudhoe Bay Unit Owners.

Dames & Moore. 1987. Kuparuk River Unit Waterflood Project Marine Life Bypass System Monitoring Program: January through December,1986. Annual Report to ARCO Alaska, Inc., and the Kuparuk River Unit Owners. June 1987.

Dames & Moore. 1988. Kuparuk River Unit Waterflood Project Marine Life Bypass System Monitoring Program. 1987 Annual Report to ARCO Alaska, Inc., and the Kuparuk River Unit Owners. February 1988.

Danks, H.V. 1990. Arctic insects: Instructive diversity. Pp. 444-470 in Canada's Missing Dimension: Science and History in the Canadian Arctic Islands, Vol. 2, C.R. Harington, ed. Ottawa: Canadian Museum of Nature.

Dau, J.R. 1986. Distribution and Behavior of Barren-Ground Caribou in Relation to Weather and Parasitic Insects. M.S. Thesis. University of Alaska, Fairbanks. 149pp.

Dau, J.R., and R.D. Cameron. 1986. Effects of a road system on caribou distribution during calving. Pp. 95-101 in Proceedings of the 4th International Reindeer/ Caribou Symposium, Whitehorse, Yukon, Canada, August 22-25, 1985, A. Gunn, F.L. Miller, and S. Skjenneberg, eds. Rangifer, Spec. Issue No. 1. Harstad, Norway: Nordic Council for Reindeer Research.

Dauphine, T.C. 1976. Biology of the Kaminuriak Population of Barren-Ground Caribou. Part 4. Growth, Reproduction, and Energy Reserves. Can. Wildl. Serv. Rep. Ser. No. 38. Ottawa: Environment Canada, Wildlife Service. 71pp.

Davies, J.R. 1997. The impact of An Offshore Drilling Platform on the Fall Migration Path of Bowhead Whales: A GIS-Based Assessment. M.S. Thesis. Western Washington University. 52 pp.

Davis, J.L., L.G. Adams, P. Valkenburg, and D.J. Reed. 1991. Relationships between body weight, early puberty, and reproductive histories in central Alaskan caribou. Pp. 115-142 in Proceedings, 4th North American Caribou Workshop, St. John's Newfoundland, Oct. 31-Nov. 3, 1989, C.E. Butler, and S.P. Mahoney, eds. St. John's, Newfoundland: Newfoundland and Labrador Wildlife Division.

Day, R.H. 1998. Predator Populations and Predation Intensity on Tundra-Nesting Birds in Relation to Human Development. Prepared for Northern Alaska Ecological Services, Fairbanks, AK, by ABR, Inc., Fairbanks, AK. May 1998.

Derksen, D.V., T.C. Rothe, and W.D. Eldridge. 1981. Use of Wetland Habitats by Birds in the National Petroleum Reserve-Alaska. U.S. Fish Wild. Serv. Resour. Publ. No. 141. Washington, DC: U.S. Dept. of the Interior, Fish and Wildlife Service. 27pp.

Derksen, D.V., W.D. Eldridge, and M.W. Weller. 1982. Habitat ecology of Pacific black brant and other geese moulting near Teshekpuk Lake, Alaska. Wildfowl 33:39-57.

Diamond, P.A., and J.A. Hausman. 1994. Contingent valuation: Is some number better than no number. J. Econ. Perspect. 8(4):45-64.

Dickens, D.F., and I.A. Buist. 1981. Oil and Gas Under Sea Ice. Prepared for Canadian Offshore Oil Spill Research Association, by Dome Petroleum Ltd, Calgary.

Dickens, D.F., and I.A. Buist. 2000. Potential Impacts of Ice Management On Oil Spill Recovery Efficiencies During Spring Break-Up. Prepared by D.F. Dickens Associates, Ltd., Escondido, CA, and S.L. Ross Environmental Research, Ottawa, Ontario, for BP Exploration (Alaska) Inc., Anchorage, AK. November 22, 2000.

Dingman, S.L., R.G. Barry, G. Weller, C. Benson, E.F. LeDrew, and C.W. Goodwin. 1980. Climate, snow cover, microclimate, and hydrology. Pp. 30-65 in An Arctic Ecosystem: The Coastal Tundra at Barrow, Alaska, J. Brown, P.C. Miller, L.L. Tieszen, and F.L. Bunnell, eds. Stroudsburg, PA: Dowden, Hutchinson and Ross, Inc.

DOE (U.S. Department of Energy). 1999. Environmental Benefits of Advanced Oil and Gas Exploration and Production Technology. DOE-FE-0385. Washington, DC: U.S. Dept. of Energy, Office of Fossil Energy.

DOI (U.S. Department of the Interior). 1972a. Final Environmental Impact Statement: Proposed Trans-Alaska Pipeline. 6 Vols. Prepared by a Special Interagency Task Force for the Federal Task Force on Alaskan Oil Development. Washington, DC: U.S. Dept. of Interior.

DOI (U.S. Department of the Interior). 1972b. Stipulations for Proposed Trans-Alaska Pipeline. Prepared by Dept. of the Interior and The Federal Task Force on Alaskan Oil Development. Washington, DC: U.S. Department of the Interior.

Dolan, T.G. 2001. Alaska Coal Gas Potential High. AAPG Explorer (June):36, 37 & 43 [Online]. Available: http://www.aapg.org/explorer/archives/2001/06jun/alaskanatgas.html [accessed April 26, 2002].

Dronenburg, R.B., J.C. George, B.D. Krogman, R.M. Sonntag, and J. Zeh. 1986. Report of the 1984 Spring Bowhead Whale (*Balaena mysticetus*) Ice-Based Visual Census. Report of the International Whaling Commission 36:293-298.

Dubielzig, R., and G. Aguirre. 1981. Morphological studies of the visual apparatus of the bowhead whale, Balaena mysticetus (RU680). Pp. 157-171 in Tissue Structural Studies and Other Investigations on the Biology of Endangered Whales in the Beaufort Sea. Final Report for the period April 1, 1980 through June 30, 1981, Vol. 1., T.F. Albert, ed. Prepared for U.S. Department of the Interior, Bureau of Land Management, Alaska OCS Office, by Department of Veterinary Science, University of Maryland, College Park, MD.

Ducks Unlimited, Inc. 1998. Waterfowl Earth Cover Selection Analysis Within the National Petroleum Reserve-Alaska. Final Report. Prepared by Ducks Unlimited, Western Regional Office, Rancho Cordova, CA, for U.S. Bureau of Land Management, Anchorage, AK. 68pp.

Dunton, H.D., E. Reimnitz, and S. Schonberg. 1982. An arctic kelp community in the Alaskan Beaufort Sea. Arctic 35(4):465-484.

Dunton, K.H. 1984. An annual carbon budget for an arctic kelp community. Pp. 311-325 in The Alaskan Beaufort Sea: Ecosystems and Environments, P.W. Barnes, D.M. Schell, and E. Reimnitz, eds. Orlando: Academic Press.

Dunton, K.H., and S. Schonberg. 1981. Ecology of the Stefansson Sound Kelp Community: Results in situ and benthic studies. Pp. 406-469 in Environmental Assessment of the Alaskan Continental Shelf, Annual Report of Principal Investigators for the Year Ending March 1981, Vol. 1. Receptors-Birds, Fish, Marine Mammals, Plankton, Littoral. Boulder, CO: U.S. Department of Commerce/ National Oceanic & Atmospheric Administration/ Office of Marine Pollution Assessment, and Bureau of Land Management, U.S. Dept. of the Interior.

Dunton, K.H., and S. Schonberg. 2000. The benthic faunal assemblage of the Boulder Patch kelp community. Pp. 371-397 in The Natural History of An Arctic Oil Field, J.C. Truett, and S.R. Johnson, eds. San Diego: Academic Press.

Durner, G.M., S.C. Amstrup, and K.J. Ambrosius. 2001. Remote identification of polar bear maternal den habitat in northern Alaska. Arctic 54(2):115-121.

Dyer, S.J., J.P. O'Neill, S.M. Wasel, and S. Boutin. 2001. Avoidance of industrial development by woodland caribou. J. Wildl. Manage. 65(3):531-542.

Ebbesson, S.O., J. Kennish, L. Ebbesson, O. Go, and J.L. Yeh. 1999. Diabetes is related to fatty acid imbalance in Eskimos. Int. J. Circumpolar Health 58(2):108-119.

Eberhardt, L.E., W.C. Hanson, J.L. Bengtson, R.A Garrott, and E.E. Hanson. 1982. Arctic fox home range characteristics in an oil-development area. J. Wildl. Manage. 46:183-190.

Eberhardt, L.E., R.A Garrott, and W.C. Hanson. 1983a. Winter movements of arctic foxes, *Alopex lagopus*, in a petroleum development area. Can. Field Nat. 97(1): 66-70.

Eberhardt, L.E., R.A Garrott, and W.C. Hanson. 1983b. Den use by arctic foxes in northern Alaska. J. Mammal. 64:97-102.

Ellison, W.T., C.W. Clark, and G.C. Bishop. 1987. Potential Use of Surface Reverberation by Bowhead Whales, Balaena mysticetus, in Under-Ice Navigation: Preliminary Considerations. Report of the International Whaling Commission 37:329-332.

Ellison, W.T., R.M. Sonntag, and C.W. Clark. 1987. Comparison of Measured Bowhead Whale, Balaena mysticetus, Migration Parameters with Results From the Tracking Algorithm. Report of the International Whaling Commission 37:309-311.

Eloranta, E., and M. Nieminen. 1986. Calving of the experimental reindeer herd in Kaamanen during 1970-1985. Pp. 115-121 in Proceedings of the 4th International Reindeer/Caribou Symposium, Whitehorse, Yukon, Canada, August 22-25, 1985, A.Gunn, F.L. Miller, and S. Skjenneberg, eds. Rangifer, Spec. Issue No. 1. Harstad, Norway: Nordic Council for Reindeer Research.

Emers, M., and J.C. Jorgenson. 1997. Effects of winter seismic exploration on tundra vegetation and the soil thermal regime in the Arctic National Wildlife Refuge, Alaska. Pp. 443-454 in Disturbance and Recovery in Arctic Lands: An Ecological Perspective, R.M.M. Crawford, ed. Dordrecht: Kluwer.

Emers, M., J.C. Jorgenson, and M.K. Raynolds. 1995. Response of arctic tundra plant communities to winter vehicle disturbance. Can. J. Bot. 73(6):905-917.

Engelhardt, F.R. 1985a. Petroleum Effects in the Arctic Environment. New York: Elsevier Applied Science. 272 pp.

Engelhardt, F.R. 1985b. Effects of petroleum on marine mammals. Pp. 217-243 in Petroleum Effects in The Arctic Environment, F.R. Engelhardt, ed. New York: Elsevier Applied Science.

Englehardt, F.R., J.R. Geraci., and T.J. Smith. 1977. Uptake and clearance of petroleum hydrocarbons in the ringed seal, *Phoca hispida*. J. Fish. Res. Board Can. 34(8): 1143-1147.

England, A.S., J.A. Estep, and W.R. Holt. 1995. Nest-site selection and reproductive performance of urban-nesting Swainson's hawks in the Central Valley of California. J. Raptor Res. 29(3):179-186.

Ens, B.J., P. Duiven, C.J. Smit, and T.M. van Spanje. 1990. Spring migration of turnstones from the Blanc D'Arguin, Mauritania. Ardea 78(1/2):310-314.

EPA (U.S. Environmental Protection Agency). 1997. The Benefits and Costs of the Clean Air Act, 1970-1990. Final Report to U.S. Congress. EPA 410-R-97-002. Office of Policy, Planning, and Evaluation, Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, DC. October.

Ercelawn, A. 1999. End of the Road -The Adverse Ecological Impacts of Roads and Logging: A Compilation of Independently Reviewed Research. Natural Resources Defense Council. December 1999. [Online]. Available: http://www.nrdc.org/land/forests/roads/eotrinx.asp [accessed Dec. 11, 2002].

Espmark, Y. 1979. Effects of maternal pre-partum undernutrition on early mother-calf relationship in reindeer. Pp. 485-496 in Proceedings of the Second International Reindeer/Caribou Symposium, Sept. 17-21, 1979, Roros, Norway, Part B, E. Reimers, E. Gaare, and S. Skjenneberg, eds. Trondheim: Direktoratet for vilt og ferskvannsfisk.

Everest Consulting Association. 2001. Technical Papers Alaska's North Slope Oilfields. Prepared by Everest Consulting Associates for the Alaska Oil and Gas Association. November 2001.

Everett, K.R. 1980. Distribution and properties of road dust along the northern portion of the Haul Road. Pp. 101-128 in Environmental Egineering and Ecological Baseline Investigations Along the Yukon River-Prudhoe Bay Haul Road, J. Brown, and R.L. Berg, eds. CRREL 80-19. Hanover, NH: U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory.

Faanes, C.A. 1987. Bird Behavior and Mortality in Relation to Power Lines in Prairie Habitats. Fish and Wildlife Technical Report 7. Washington, DC: U.S. Dept. of the Interior, Fish and Wildlife Service.

Fairweather E&P Services, Inc. 2000. Historical Blowout Study: North Slope, Alaska. Prepared by Fairweather E&P Services, Inc., Anchorage, AK, for BP-Amoco Exploration, AK. June 2000.

Fancy, S.G. 1983. Movements and activity budgets of caribou near oil drilling sites in the Sagavanirktok river floodplain, Alaska. Arctic 36:193-197.

Fancy, S.G., and R.G. White. 1985a. Energy expenditures by caribou while cratering in snow. J. Wildl. Manage. 49(4):987-993.

Fancy, S.G., and R.G. White. 1985b. The incremental cost of activity. Pp. 143-159 in Bioenergetics of Wild Herbivores, R.J. Hudson, and R.G. White, eds. Boca Raton: CRC.

Fancy, S.G., and K.R. Whitten. 1991. Selection of calving sites by Porcupine herd caribou. Can. J. Zool. 69(7):1736-1743.

Fancy, S.G., L.F. Pank, K.R. Whitten, and W.L. Regelin. 1989. Seasonal movements of caribou in arctic Alaska as determined by satellite. Can. J. Zool. 67(3):644-650.

Fay, F.H. 1974. The role of ice in the ecology of marine mammals of the Bering Sea. Pp. 383-389 in Oceanography of the Bering Sea: With Emphasis on Renewable Resources, D.W. Hood, and E.J. Kelley, eds. Occasional Publ. No 2. Institute of Marine Science, University of Alaska, Fairbanks.

Fechhelm, R.G. 1999. The effect of new breaching in a Prudhoe Bay causeway on the coastal distribution of humpback whitefish. Arctic 52(4):385-393.

Fechhelm, R.G., and D.B. Fissel. 1988. Wind-aided recruitment of Canadian arctic cisco (*Coregonus autumnalis*) into Alaskan waters. Can. J. Fish. Aquat. Sci. 45:906-910.

Fechhelm, R.G., and W.B. Griffiths. 1990. The effect of wind on the recruitment of Canadian arctic cisco (*Coregonus autumnalis*) into the central Alaskan Beaufort Seas. Can. J. Fish. Aquat. Sci. 47(11):2164-2171.

Fechhelm, R.G., P.C. Craig, J.S. Baker, and B.J. Gallaway. 1984. Fish Distribution and Use of Nearshore Waters in the Northeastern Chukchi Sea. Final Report. Prepared for National Oceanic and Atmospheric Administration, OMPA/ OCSEAP Juneau, AK, by LGL Ecological Research Associates, Inc., Bryan, TX. February 1984.

Fechhelm, R.G., J.S. Baker, W.B. Griffiths, and D.R. Schmidt. 1989. Localized movement patterns of least cisco (*Coregonus sardinella*) and arctic cisco (*C. autumnalis*) in the vicinity of a solid-fill causeway. Pp. 75-106 in Research Advances on Anadromous Fish in Arctic Alaska and Canada, D.W. Norton, ed. Biological Papers of the University of Alaska 24. Fairbanks: Institute of Arctic Biology, University of Alaska.

Fechhelm et al. 2000. The 1999 Point Thomson Unit Nearshore Marine Fish Study. Report by LGL Alaska Research Associates to BP Exploration (Alaska). Anchorage, AK.

Fechner, S.A. 1991. Port sites critical to developing minerals. Minerals Today (June): 10-11 [Online]. Available: http://imcg.wr.usgs.gov/usbmak/mt1a.html [accessed Dec. 2, 2002].

Feder, H.M., and S.G. McGee. 1982. Prudhoe Bay Waterflood Project Environmental Monitoring Program. Prepared by Institute of Marine Science, University of Alaska, Fairbanks, AK, for U.S. Dept. of the Army, Alaska District, Corps of Engineers, Anchorage, AK.

Felix, N.A., and M.K. Raynolds. 1989a. The effects of winter seismic trails on tundra vegetation in northeastern Alaska, U.S.A. Arct. Alp. Res. 21(2):188-202.

Felix, N.A., and M.K. Raynolds. 1989b. The role of snow cover in limiting surface disturbance caused by winter seismic exploration. Arctic 42(1):62-68.

Felix, N. A., M.K. Raynolds, J.C. Jorgenson, and K.E. DuBois. 1992. Resistance and resilience of tundra plant communities to disturbance by winter seismic vehicles. Arct. Alp. Res. 24(1):69-77.

Ferrero, R.C., D.P. DeMaster, P.S. Hill, M.M. Muto, and A.L. Lopez. 2000. Alaska Marine Mammal Stock Assessments, 2000. NOAA Tech. Memo. NMFS-AFSC 119. Seattle, WA: U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Alaska Fisheries Science Center. 191 pp.

Ferrians, O.J., R. Kachadoorian, and G.W. Greene. 1969. Permafrost and Related Engineering Problems in Alaska. U.S. Geological Survey Professional Paper 678. Washington, DC: U.S. Govt. Print. Off.

Field, D.R., and W.R. Birch. 1988. Rural Sociology and the Environment. New York: Greenwood Press.

Field, D.R., and W.R. Burch, Jr. 1991. Rural Sociology and the Environment. New York: Greenwood Press.

Fink, T.R. 1983. Letter from T.R. Fink, Manager, Environmental Conservation of ARCO Alaska Inc., Anchorage, AK, to Harold M. Scott, Drinking Water Programs Branch, U.S. Environmental Protection Agency, Region X, Seattle, WA. December 3, 1983.

Flint, P.L., and J.B. Grand. 1999. Incubation behavior of Spectacled eiders on the Yukon-Kuskokwim Delta, Alaska. Condor 101(2):413-416.

Forbes, B.C., J.J. Ebersole, and B. Strandberg. 2001. Anthropogenic disturbance and patch dynamics in circumpolar arctic ecosystems. Conserv. Biol. 15(4):954-969.

Forsyth, C.J., and D.K. Gauthier. 1991. Families of offshore oil workers: Adaptations to cyclical father absence/presence. Sociological Spectrum 11:177-202.

Freeman, A.M. III. 1993. The Measurement of Environmental and Resource Values: Theory and Methods. Washington, DC: Resources for the Future.

French, H.M. 1985. Surface disposal of waste-drilling fluids, Ellef Ringnes Island, N.W.T.: Short-term observations. Arctic 38(4):292-302.

Freudenburg, W.R. 1986. The density of Acquaintanceship: An overlooked variable in community research. Am. J. Sociol. 92(1):27-63.

Freudenburg, W.R., and R. Gramling. 1992. Community impacts of technological change: Toward a longitudinal perspective. Social Forces 70:937-957.

Freudenburg, W.R., and R. Gramling. 1998. Linked to what? Economic linkages and an extractive economy. Soc. Nat. Resour. 11(6):569-586.

Frost, K.J., and L.F. Lowry. 1983. Demersal Fishes and Invertebrates Traweled in the Northeastern Chukchi and Western Beaufort Seas, 1976-77. NOAA Technical Report NMFS SSRF-764. Seattle, WA: National Oceanic and Atmospheric Administration.

Frost, K.J., and L.F. Lowry. 1984. Trophic relationships of vertebrate consumers in the Alaskan Beaufort Sea. Pp. 381-401 in The Alaskan Beaufort Sea: Ecosystems and Environments, P.W. Barnes, D.M. Schell, and E. Reimnitz, eds. Orlando: Academic Press.

Frost, K.J., and L.E. Lowry. 1988. Effects of industrial activities on ringed seals in Alaska, as indicated by aerial surveys. Pp. 15-25 in Port and Ocean Engineering under Arctic Conditions, Vol. 2., W.M. Sackinger, and M.O. Jeffries, eds. Fairbanks, AK: Geophysical Institute, University of Alaska.

Frost, K.J., L.F. Lowry, J.R. Gilbert, and J.J Burns. 1988. Ringed Seal Monitoring: Relationships of Distribution and Abundance to Habitat Attributes and Industrial Activities. Anchorage, AK: U.S. Minerals Management Service. 101 pp.

Frost, K.J., L.F. Lowry, E.H. Sinclair, J. Ver Hoef, and D.C. McAllister. 1994a. Impacts on distribution, abundance, and productivity of harbor seals. Pp. 97-118 in Marine Mammals and the Exxon Valdez, T.R. Loughlin, ed. San Diego: Academic Press.

Frost, K.J., C.A. Manen, and T.L. Wade. 1994b. Petroleum hydrocarbons in tissues of harbor seals from Prince William Sound and the Gulf of Alaska. Pp. 331-358 in Marine Mammals and the Exxon Valdez, T.R. Loughlin, ed. San Diego: Academic Press.

Frost, K.J., L.F. Lowry, G. Pendleton, and H.R. Nute. 2002. Monitoring Distribution and Abundance of Ringed Seals in Northern Alaska. OCS Study MMS 2002-043. Final Report from the Alaska Department of Fish and Game, Juneau, AK, for U.S. Mineral Management Service, Anchorage, AK. 66 pp + appendices.

Fuller, A.S., and J.C. George. 1997. Evaluation of Subsistence Harvest Data from the North Slope Borough 1993 Census for Eight North Slope Villages: For the Calendar Year 1992. Department of Wildlife Management, North Slope Borough, Barrow, AK.

Furgal, C.M., S. Innes, and K.M. Kovacs. 1996. Characteristics of ringed seal, Phoca hispida, subnivean structures and breeding habitat and their effects on predation. Can. J. Zool. 74(5):858-874.

Furniss, R.A. 1975. Prudhoe Bay Study: Inventory and cataloging of arctic area waters. Pp. 31-47 in Federal Aid in Fish Restoration, 1974-1975, Vol. 16, Study G-I-1, Alaska Department of Fish and Game, Sport Fishing Division, Juneau, AK.

FWS (U.S. Fish and Wildlife Service). 1986. Arctic National Wildlife Refuge Coastal Plain Resource Assessment. Final Report. Baseline Study of the Fish, Wildlife, and Their Habitats, Section 1002C, Alaska National Interest Lands Conservation Act, Vol. 1, G.W. Garner, and P.E. Reynolds, eds. U. S. Fish and Wildlife Service, Region 7, Anchorage, AK.

FWS (U.S. Fish and Wildlife Service). 1987. Comparison of Actual and Predicted Impacts of the Trans-Alaska Pipeline System and the Prudhoe Bay Oilfields on the North Slope of Alaska. U.S. Fish and Wildlife Service, Fairbanks Fish and Wildlife Enhancement Office, Fairbanks, AK. December 1987.

FWS (U.S. Fish and Wildlife Service). 1995a. A Preliminary Review of The Arctic National Wildlife Refuge, Alaska, Coastal Plain Resouce Assessment: Report and Recommendation to the Congress of the United States and Final Legislative Environmental Impact Statement, August 29, 1995. U.S. Fish and Wildlife Service, U.S. Dept. of the Interior, Anchorage, AK.

FWS (U.S. Fish and Wildlife Service). 1995b. Habitat Conservation Strategy for Polar Bears in Alaska. Anchorage, AK: U. S. Fish and Wildlife Service. 119 pp.

FWS (U.S. Fish and Wildlife Service). 1998. Stock Assessment for Polar Bear (Ursus maritimus)- Alaska Chukchi/Bering Seas Stock and Southern Beaufort Sea Stock. Marine Mammals Management, U.S. Fish and Wildlife Service, Anchorage, AK. 35pp.

FWS (U.S. Fish and Wildlife Service). No date. Arctic National Wildlife Refuge web site, http://arctic.fws.gov. Last accessed 2/27/03.

Galginaitis, M., C. Gerlach, P. Bowers, and C. Wooley. 2001. Subsistence. Section 3.3.3. in Environmental Report for Trans-Alaska Pipeline System Right-of-Way Renewal, Vol.1.

Trans Alaska Pipeline System Owners [Online]. Available: http://tapseis.anl.gov/documents/docs/Section_33_May2.pdf [accessed Nov. 27, 2002].

Gallant, A.L., E.F. Binnian, J.M. Omernick, and M.B. Shasby. 1995. Ecoregions of Alaska. Professional Paper 1567. Reston, VA: U.S. Geological Survey.

Gallaway, B.J., and R.G. Fechhelm. 2000. Anadromous and amphidromous fishes. Pp. 349-369 in The Natural History of An Arctic Oil Field, J.C. Truett, and S.R. Johnson, eds. San Diego: Academic Press.

Gallaway, B.J., W.B. Griffiths, P.C. Craig, W.J. Gazey, and J.W. Helmericks. 1983. An assessment of the Colville river delta stock of arctic cisco—migrants from Canada? Biological Papers of the University of Alaska 21:4-23.

Gallaway, B.J., W.J. Gazey, and L.L. Moulton. 1989. Population trends for the arctic cisco (*Coregonus autumnalis*) in the Colville river of Alaska as reflected by the commercial fishery. Pp. 153-165 in Research Advances on Anadromous Fish in Arctic Alaska and Canada, D.W. Norton, ed. Biological Papers of the University of Alaska No. 24. Fairbanks: Institute of Arctic Biology, University of Alaska.

GAO (U.S. General Accounting Office). 1994. Offshore Oil and Gas Resources: Interior Can Improve Its Management of Lease Abondonment. GAO/RCED-94-82. Washington, DC: U.S. General Accounting Office.

GAO (U.S. General Accounting Office). 2002. Alaska's North Slope, Requirements for Restoring Lands After Oil Production Ceases. GAO-02-357. Washington, DC: U.S. General Accounting Office.

Garrott, R.A., L.E. Eberhardt, and W.C. Hanson. 1983. Summer food habits of juvenile arctic foxes in northern Alaska Alopex lagopus. J. Wildl. Manage. 47(2):540-545.

Gavin, A. 1978. Caribou Migrations and Patterns, Prudhoe Bay Region, Alaska's North Slope, 1969-1977. Prepared for Atlantic Richfield Company.

Gentlemen, R., and J.E. Zeh. 1987. A statistical model for estimating the number of bowhead whales, *Balaena mysticetus*, passing a census point from combined visual and acoustic data. Report of the International Whaling Commission 37: 313-327.

George, J.C., and R. Kovalsky. 1986. Observations on the Kupigruak Channel (Colville River) Subsistence Fishery, October 1985. Department of Wildlife Management, North Slope Borough, Barrow, AK. 60pp.

George, J.C., and B.P. Nageak. 1986. Observations on the Colville River Subsistence Fishery at Nuiqsut, Alaska: For the period 4 July-1 November 1984. Department of Wildlife Management, North Slope Borough, Barrow, AK. 35pp.

George, J.C., L.M. Philo, G.M. Carroll, and T.F. Albert. 1988. 1987 subsistence harvest of bowhead whales, *Balaena mysticetus*, by Alaskan Eskimos. Report of the International Whaling Commission 38:389-392.

George, J.C., C. Clark, G.M. Carroll, and W.T. Ellison. 1989. Observations on the ice-breaking and ice navigation behavior of migratory bowhead whales *Balaena mysticetus* near Pt. Barrow, Alaska, spring 1985. Arctic 42(1):24-30.

George, J.C., R. Suydam, L.M. Philo, T. Albert, J. Zeh, and G. Carroll. 1995. Report of the Spring 1993 Census of Bowhead Whales, Balaena mysticetus, off Point Barrow, Alaska With Observations on the 1993 Subsistence Hunt of Bowhead Whales by Alaska Eskimos. Report of the International Whaling Commission 45: 371-384.

George, J.C., J. Badda, J. Zeh, L. Scott, S. Brown, T. O'Hara, and R. Suydam. 1999. Age and growth estimates of bowhead whales, *Balaena mysticetus*, via aspartic acid racemization. Can. J. Zool. 77(4):571-580.

Geraci, J.R. 1990. Physiologic and toxic effects on cetaceans. Pp. 167-197 in Sea Mammals and Oil: Confronting the Risks, J.R. Geraci, and D.J. St. Aubin, eds. San Diego: Academic Press.

Geraci, J.R., and D.J. St. Aubin. 1982. Study of the Effects of Oil on Cetaceans. Final Report. Guelph: University of Guelph. 274 pp.

Geraci, J.R., and D.J. St. Aubin. 1985. Expanded Studies of the Effects of Oil on Cetaceans. Final Report. Contract 14-12-001-001-29169. Prepared for U.S. Department of the Interior, Minerals Management Service, Washington, DC., by University of Guelph, Guelph, Ontario.

Geraci, J.R., and St. Aubin, eds. 1990. Sea Mammals and Oil: Confronting the Risks. San Diego: Academic Press. 282 pp.

Geraci, J.R., and T.G. Smith. 1976. Direct and indirect effects of oil on the ringed seals (*Phoca hispida*) of the Beaufort Sea. J. Fish. Res. Board Can. 33(9):1976-1984.

Gerhart, K.L., R.G. White, R.D. Cameron, and D.E. Russell. 1996. Body composition and nutrient reserves of arctic caribou. Can. J. Zool. 74(1):136-146.

Gerhart, K.L., D.E. Russell, D. van de Wetering, R.G. White, and R.D. Cameron. 1997a. Pregnancy of adult caribou (*Rangifer tarandus*): Evidence for lactational infertility. J. Zool. (Lond) 242:17-30.

Gerhart, K.L., R.G. White, R.D. Cameron, D.E. Russell, and D. van de Wetering. 1997b. Pregnancy rate as an indicator of nutritional status in *Rangifer*: implications of lactational infertility. Rangifer 17(1):21-24.

Gilders, M.A., and M.A. Cronin. 2000. North Slope oil field development. Pp. 15-33 in The Natural History of An Arctic Oil Field, J.C. Truett, and S.R. Johnson, eds. San Diego: Academic Press.

Gilmore, J.S. 1976. Boom towns may hinder energy resource development. Science 191(4227):535-540.

Goodale, D.R. 1981. The Temporal and Geographic Distribution of Humpback, Finback and Right Whale Calves. M.S. Thesis. University of Rhode Island, Kingston, RI.

Gotmark, F., R. Neergaard, and M. Ahlund. 1989. Predation of artificial and real arctic loon nests in Sweden. J. Wildl. Manage. 54:515-522.

Gotthardt, T., and R. Lanctot. 2002. Status Report on the Buff-breasted Sandpiper (*Tryngites subruficollis*). U.S. Fish and Wildlife Service, Ecological Services, Anchorage, AK.

Gramling, R. 1989. Concentrated work scheduling: Enabling and constraining aspects. Sociol. Perspect. 32:47-64.

Gramling, R. 1996. Oil on the Edge: Offshore Development, Conflict, Gridlock. Albany: State University of New York Press.

Gramling, R., and S. Brabant. 1986. Boom towns and offshore energy impact assessment: The development of a comprehensive model. Sociol. Perspect. 29:177-201.

Gramling, R., and C. Forsyth. 1987. Work scheduling and family interaction: A theoretical perspective. J. Fam. Issues 8(2):163-175.

Gramling, R., and W.R. Freudenburg. 1992a. Opportunity-threat, development, and adaptation: Toward a comprehensive framework for social impact assessment. Rural Sociol. 57(2):216-234.

Gramling, R., and W.R. Freudenburg. 1992b. The *Exxon Valdez* oil spill in the context of U.S. petroleum politics. Ind. Crisis Quart. 6(3):175-196.

Grand, J.B., and P.L. Flint. 1997. Productivity of nesting Spectacled eiders on the lower Kashunuk River, Alaska. Condor 99(4):926-932.

Grantz, A., S.D. May, and P.E. Hart. 1994. Geology of the Arctic continental margin of Alaska. Pp. 17-48 in The Geology of Alaska, G. Plafker, and H.C. Berg, eds. The Geology of North America, Vol. G-1. Boulder, CO: Geological Society of America.

Griffith, B., D.C. Douglas, D.E. Russell, R.G. White, T.R. McCabe, and K.R. Whitten. 2000a. Effects of recent climate warming on caribou habitat and calf survival. Pp. 65 in Proceedings of the 8th North American Caribou Workshop, Whitehorse, Yukon, Canada, April 20-24, 1998, R. Farnell, D. Russell, and D. van de Wetering, eds. Rangifer Spec. Issue 12. Tromso, Norway: Nordic Council for Reindeer Research.

Griffith, B., R.G. White, R.D. Cameron, D.E. Russell, and T.R. McCabe. 2000b. A methodology for predicting effects of displacement on caribou populations: integrating behavior, habitat value, and population dynamics. Pp. 105 in Proceedings of the 8th North American Caribou Workshop, Whitehorse, Yukon, Canada, April 20-24, 1998, R. Farnell, D. Russell, and D. van de Wetering, eds. Rangifer Spec. Issue 12. Tromso, Norway: Nordic Council for Reindeer Research.

Griffith, B., D.C. Douglas, N.E. Walsh, D.D. Young, T.R. McCabe, D.E. Russell, R.G. White, R.D. Cameron, and K.R. Whitten. 2002. The Porcupine caribou herd-Part 1. Section 3 in Arctic Refuge Coastal Plain Terrestrial Wildlife Research Summaries, D.C. Douglas, and P.E. Reynolds, eds. Biological Science Report USGS/BRD/BSR-2002-0001. U.S. Geological Survey, Biological Resources Division [Online]. Available: http://alaska.usgs.gov/BSR-2002/usgs-brd-bsr-2002-001.html [accessed Dec. 5, 2002].

Griffiths et al. 2002. Nearshore Beaufort Sea Fish Studies in the Point Thomson Area, 2001. Report by LGL to BP Exploration (Alaska) and the Point Thomson Unit Partners, Anchorage, AK.

Griffiths, W.B., and R.E. Dillinger. 1981. Part 5. Invertebrates. Pp. 1-198 in Beaufort Sea Barrier Island-Lagoon Ecological Process Studies. Final report. Simpson Lagoon. Environmental Assessment of the Alaskan Continental Shelf, Final Report of Principal Investigators, Vol. 8. Biological Studies. Bureau of Land Management and National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Boulder, CO.

Griffiths, W.B., D.R. Schmidt, R.G. Fechhelm, B.J. Gallaway, R.E. Dillinger Jr., W. Gazey, W.H. Neill, and J.S. Baker. 1983. Environmental Summer Studies (1982) for the Endicott Development, Vol. 3. Fish Ecology, B.J. Gallaway, and R.P. Britch, eds. Report by LGL Alaska Research Associates, Inc., and Northern Technical Services, for Sohio Alaska Petroleum Company, Anchorage, AK.

Groves, D.J., B. Conant, R.J. King, J.I. Hodges, and J.G. King. 1996. Status and trends of loon populations summering in Alaska, 1971-1993. Condor 98(2):189-195.

Grubb, T.G., and W.W. Bowerman. 1997. Variations in breeding bald eagle responses to jets, light planes and helicopters. J. Raptor Res. 31(3):213-222.

Gryc, G., ed. 1988. Geology and Exploration of the National Petroleum Reserve in Alaska, 1974 to 1982. U.S. Geol. Survey Prof. Paper 1399. Washington, DC: U.S. G.P.O.

Guilders, M.A., and M.A. Cronin. 2000. North Slope oil field development. Pp. 15-33 in The Natural History of An Arctic Oil Field, J.C. Truett, and S.R. Johnson, eds. San Diego: Academic Press.

Hachmeister, L.E., D.R. Glass, and T.C. Cannon. 1991. Effects of solid-fill gravel causeways on the coastal central Beaufort Sea environment. Pp. 81-96 in Fisheries and Oil Development on the Continental Shelf, C.S. Benner, and R.W. Middleton, eds. American Fisheries Society Symposium 11. Bethesda, MD: American Fisheries Society.

Haldiman, J.T., Y.Z. Abdelbaki, F. Al-Bagdadi, D.W. Duffield, W.G. Henk, and R.W. Henry. 1981. Determination of the gross and microscopic structure of the lung, kidney, brain and skin of the bowhead whale, Balaena mysticetus. Pp. 305-662 in Tissue Structural Studies and Other Investigations on the Biology of Endangered Whales in the Beaufort Sea. Final Report for the period April 1, 1980 through June 30, 1981, Vol. 1., T.F. Albert, ed. Prepared for U.S. Department of the Interior, Bureau of Land Management, Alaska OCS Office, by Department of Veterinary Science, University of Maryland, College Park, MD.

Haldiman, J.T., Y.Z. Abdelbaki, D.W. Duffield, W.G. Henk, and R.W. Henry. 1982. Studies on the Morphology of the Skin, Baleen, Respiratory System, Urinary System, Vascular System, Brain, and Eye of the Bowhead Whale, *Balaena mysticetus*. Final Report for the period 1 Sept. 1981 through 31 Aug. 1982 to the North Slope Borough, Barrow, AK, from the Department of Veterinary Anatomy and Fine Structure, School of Veterinary Medicine, Louisiana State University, Baton Rouge, LA. 159pp.

Haldiman, J.T., W.G. Henk, R.W. Henry, T.F. Albert, Y.Z. Abdelbaki, and D.W. Duffield. 1985. Epidermal and papillary dermal characteristics of the bowhead whale, *Balaena mysticetus*. Anat. Rec. 211(4):391-402.

Haldiman, J.T. et al. 1986. Continued Studies on the Morphology of the Skin, Respiratory System, Urinary System, Brain and Eye of the Bowhead Whale, *Balaena mysticetus*. Final Report for the period 1 Sept. 1981 through 30 June 1985 to the North Slope Borough, Barrow, AK, from the Department of Veterinary Anatomy and Fine Structure, School of Veterinary Medicine, Louisiana State University, Baton Rouge, LA. 155 pp.

Hale, D.A., M.J. Hameedi, L.E. Hachmeister, and W.J. Stringer. 1989. Effects of the West Dock Causeway on Nearshore Oceanographic Processes in the Vicinity of Prudhoe Bay, Alaska. Special Report for the USEPA. NOAA,Anchorage, AK. 50pp.

Hall Jr., E.S., S.C. Gerlach, and M.B. Blackman. 1985. In the National Interest: A Geographically Based Study of Anaktuvul Pass Inupiat Subsistence Trough Time. North Slope Borough, Barrow, AK.

Hall, J.D., M. Gallagher, K. Brewer, P. Regos, and P. Isert. 1994. 1993 Kuvlum Exploration Area Site Specific Monitoring Program. Prepared for ARCO Alaska, Inc., Anchorage, AK, by Coastal and Offshore Pacific Corporation, Walnut Creek, CA.

Hanawa, S. 1985. Results of the nationwide counts of waders in Japan. 1. Annual changes in the species and numbers of waders (1983-1985). Strix 4:76-87.

Hanemann, W.M. 1994. Valuing environment through contingent valuation. J. Econ. Perspect. 8(4):19-44.

Hansen, D.J. 1985. The Potential Effects of Oil Spills and Other Chemical Pollutants on Marine Mammals Occurring in Alaskan Waters. OCS Report MMS 85-0031. Anchorage, AK: U.S. Dept. of the Interior, Minerals Management Service, Alaska Outer Continental Shelf Region. 22pp.

Hansen, J., and S. Lebedeff. 1987. Global trends of measured surface air temperature. J. Geophys. Res. 92:13345-13372.

Hansen, J., R. Ruedy, J. Glascoe, and M. Sato. 1999. GISS analysis of surface temperature change. J. Geophys. Res. 104(24):30997-31022.

Hanski, I., and M.E. Gilpin. 1997. Metapopulation Biology: Ecology, Genetics, and Evolution. San Diego, CA: Academic Press.

Harcharek, R. 1995. North Slope Borough 1993-1994 Economic Profile and Census Report. Vol. 7. George N. Ahmaogak, Sr., Mayor. North Slope Borough, Department of Planning and Community Services, Barrow, Alaska.

Harris, R.E., G.W. Miller, and W.J. Richardson. 2001. Seal responses to airgun sounds during summer seismic surveys in the Alaskan Beaufort Sea. Mar. Mamm. Sci. 17(4):795-812.

Harrison, W.D., and T.E. Osterkamp. 1978. Heat and Mass Transport Processes in Subsea Permafrost: 1. An Analysis of Molecular Diffussion and Its Consequences. J. Geophys. Res. 83(C9). Fairbanks: Alaska Sea Grant Program.

Harvey, J.T., and M.E. Dahlheim. 1994. Cetaceans in oil. Pp. 257-264 in Marine Mammals and the Exxon Valdez, T.R. Loughlin, ed. San Diego: Academic Press.

Haugen, R.K. 1982. Climate of Remote Areas in North-Central Alaska 1975-1979 Summary. CRREL Report 82-35. Prepared for Office of the Chief of Engineers, by U.S. Army, Corps of Engineers, Cold Regions Research and Engineering Laboratory.

Haukioja, E., and R. Salovaara. 1978. Summer weight of reindeer (*Rangifer tarandus*) calves and its importance for their future survival. Rep. Kevo Subarctic 14:1-4.

Hausman, J.A. 1993. Contingent Valuation: A Critical Assessment. Amsterdam: North Holland Press.

Haynes, T., and S. Pedersen. 1989. Development and subsistence: Life after oil. Alaska Department of Fish and Game 21(6):24-27.

Hazen, B. 1997. Use of ice roads and ice pads for Alaskan arctic oil exploration projects. Pp. 1-11 to 1-13 in NPR-A Symposium Proceedings: Science, Traditional Knowledge, and the Resources of the Northeast Planning Area of the National Petroleum Reserve - Alaska, April 16-18, 1997, Anchorage, AK, K.L. Mitchell, ed. OCS Study MMS 97-0013. Anchorage, AK: U.S. Dept. of the Interior, Mineral Management Service, Alaska OCS Region.

Hazen, B. 1999. ARCO Alpine Project, Wellpad Geothermal Design Report. Final Report. Prepared by Northern Engineering & Scientific, Anchorage, AK. February 2, 1999.

Hazen, C.B., D.L. Miller, M.J. Stanley, and W.S. Powell. 1994. Design, Construction and Operation of an Insulated Ice Drilling Pad, North Slope, Alaska. Paper presented at the 7th International ASCE Cold Regions Specialty Conference, Edmonton, Alberta, March 1994.

Helle, T., and L. Tarvainen. 1984. Effects of insect harassment on weight gain and survival in reindeer (Rangifer tarandus) calves. Rangifer 4(1):24-27.

Helle, T., J. Aspi, K. Lempa, and E. Taskinen. 1992. Strategies to avoid biting flies by reindeer: Field experimens with silhouette traps. Ann. Zool. Fenn. 29(2):69-74.

Hemming, C.R. 1988. Aquatic Habitat Evaluation of Flooded North Slope Gravel Mine Sites (1986-1987). Technical Report No. 88-1. Habitat Division, Alaska Department of Fish and Game, Juneau, AK. 69pp.

Hemming, C.R. 1993. Tundra Stream Fish Habitat Investigations in the North Slope Oilfields. Technical Report No. 93-1. Habitat and Restoration Division, Alaska Department of Fish and Game, Juneau, AK. 64pp.

Hemming, C.R. 1995. Fisheries Enhancement Investigations in the Prudhoe Bay and Kuparuk River Oilfields, 1993. Technical Report No. 95-3. Habitat and Restoration Division, Alaska Department of Fish and Game, Juneau, AK. 62pp.

Hemming, C.R., P.K. Webber, and J.F. Winters. 1989. Limnological and Fisheries Investigations of Flooded North Slope Gravel Mine Sites, 1988. Technical Report No. 89-1. Habitat and Restoration Division, Alaska Department of Fish and Game, Juneau, AK. 60pp.

Henk, W.G., and D.L. Mullan. 1996. Common epidermal lesions of the bowhead whale, Balaena mysticetus. Scanning Microsc.10(3):905-916.

Henry, G.H.R., and U. Molau. 1997. Tundra plants and climate change: The International Tundra Experiment (ITEX). Global Change Biol. 3(Suppl. 1):1-9.

Hepa, R.T., H.K. Brower, and D. Bates. 1997. North Slope Borough Subsistence Harvest Documentation Project: Data for Atqasuk, Alaska For the Period July 1, 1994 to June 30, 1995. Technical Report. Department of Wildlife Management, North Slope Borough. Barrow, AK. 42pp.

Hernandez, H. 1973. Natural plant recolonization of surficial disturbances, Tuktoyaktuk Peninsula region, Northwest Territories. Can. J. Bot. 51:2177-2196.

Hershey, A.E., G.M. Gettel, M.E. McDonald, M.C. Miller, H. Mooers, W.J. O'Brien, J. Pastor, C. Richards, and J.A. Schuldt. 1999. A geomorphic-trophic model for landscape control of arctic lake food webs. Bioscience 49(11):887-897.

Heuer, C.E., E.L. Long, and J.P. Zarling. 1985. Passive Techniques for ground temperature control. Pp. 72-154 in Thermal Design Considerations in Frozen Ground Engineering: A State of the Practice Report, T.G. Krzewinski, and R.G. Tart, Jr., eds. New York: American Society of Civil Engineers.

Hok, J.R. 1969. A Reconnaissance of Tractor Trails and Related Phenomena on the North Slope of Alaska. Washington, DC: U.S. Bureau of Land Management.

Hok, J.R. 1971. Some Effects of Vehicle Operation on Alaskan Arctic Tundra. M.S. Thesis. University of Alaska, Fairbanks.

Hopkins, D.M. 1949. Thaw lakes and thaw sinks in the Imurok Lake area, Seward Peninsula, Alaska. J. Geol. 57:119-131.

Horner, R.A. 1981. Beaufort Sea plankton studies. Pp. 65-314 in Environmental Assessment of the Alaskan Continental Shelf. Final Report of Principal Investigators, Vol. 13. Biological Studies. Boulder, CO: U.S. Department of Commerce/ National Oceanic & Atmospheric Administration/ Office of Marine Pollution Assessment, and Bureau of Land Management, U.S. Dept. of the Interior.

Horner, R. 1984. Phytoplankton abundance, Chlorophyll a, and primary productivity in the western Beaufort Sea. Pp. 295-310 in The Alaskan Beaufort Sea: Ecosystems and Environments, P.W. Barnes, D.M. Schell, and E. Reimnitz, eds. Orlando: Academic Press.

Horner, R.A., and V. Alexander. 1972. Ecology and Metabolism of Sea Ice Organisms. Report R72-6. Institute of Marine Science, University of Alaska.

Horner, R.A, and G.C. Schrader. 1982. Relative contribution from ice algae, phytoplankton, and benthic microalgae to primary production in nearshore regions of the Beaufort Sea. Arctic 35(4):485-503.

Horowitz, A., A. Sexstone, and R.M. Atlas. 1978. Hydrocarbons and microbial activities in sediment of an arctic lake one year after contamination with leaded gasoline. Arctic 31(3):180-191.

Houghton, J.T., L.G. Meira Filho, J. Bruce, H. Lee, B.A. Callander, E. Haites, N. Harris, and K. Maskell. 1995. Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios. Cambridge: Cambridge University Press.

Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell. 1996. Climate Change 1995: The Science of Climate Change. Cambridge: Cambridge University Press.

Howe, A.L., R.J. Walker, C. Olnes, K. Sundet, and A.E. Bingham. 2001. Participation, Catch, and Harvest in Alaska Sport Fisheries During 1999. Fishery Data Series 01-8. Anchorage, AK: Alaska Department of Fish and Game, Division of Sport Fish, Research and Technical Services. June 2001.

Humphrey, B., D.R. Green, B.R. Fowler, D. Hope, and P.D. Boehm. 1987. The fate of oil in the water column following experimental oil-spills in the arctic marine nearshore. Arctic 40(Supp. 1):124-132.

Huntington, H.R. 2000. Using traditional ecological knowledge in science: Methods and applications. Ecol. Appl. 10(5):1270-1274.

IAI. 1990a. Subsistence Resources Harvest Patterns: Kaktovik. Social and Economic Studies Program Special Report No. 9. Mineral Management Service, Alaska OCS Region, Anchorage, AK.

IAI. 1990b. Subsistence Resources Harvest Patterns: Nuiqsut. Social and Economic Studies Program Special Report No. 8. Mineral Management Service, Alaska OCS Region, Anchorage, AK.

Intec Engineering. 1998. Lagoon Permafrost – Northstar Development Project Detailed Engineering. Intec Project No. H-0660.03. Technical Note TN450, Rev.3. Prepared for BP Exploration (Alaska), Inc., Anchrage, AK. May 1998.

Intec Engineering. 1999. Northstar Development Project, Buried Leak Detection System Preliminary Design and System Description. Intec Project No. H-0660.03. Prepared for BP Exploration (Alaska), Anchorage, AK. August 1999.

Interorganizational Committee on Guidelines and Principles. 1994. Guidelines and Principles for Social Impact Assessment. NOAA Tech. Memo. NMFS-F/SPO-16. U.S. Department of Commerce. 29pp.

IWC (International Whaling Commission). 1988. Report of the Scientific Committee. Report of the International Whaling Commission 38:32-155. (see pp. 49-50).

IWC (International Whaling Commission). 1997. Chairman's Report of the Forty-eight Annual Meeting. Report of the International Whaling Commission 47:17-55. (see pp. 24).

Jaffe, D.A., R.E. Honrath, D. Furness, T.J. Conway, E. Dlugokencky, and L.P. Steele. 1995. A determination of the CH4, NOx, and CO2 emission from the Prudhoe Bay, Alaska Oil Development. J. Atmos. Chem. 20:213-227.

Jakimchuk, R.D., S.H. Ferguson, and L.G. Sopuck. 1987. Differential habitat use and sexual segregation in the Central Arctic caribou herd. Can. J. Zool. 65(3):534-541.

Jamison, H.C., L.D. Brockett, and R.A. McIntosh. 1980. Prudhoe Bay – A 10-Year Perspective. Pp. 289-314 in Giant Oil and Gas Fields of the Decade 1968-1978, M.T. Halbouty, ed. Tulsa: American Association of Petroleum Geologists.

Johannessen, O.M., E.V. Shalina, and M.W. Miles. 1999. Satellite evidence for an Arctic sea ice cover in transformation. Science 286(5446):1937-1939.

Johnson, M.W. 1956. The Plankton of the Beaufort and Chukchi Sea Areas of the Arctic and Its Relation to the Hydrography. Technical Paper No. 1. Montreal: Arctic Institute of North America.

Johnson, L.A. 1981. Revegetation and Selected Terrain Disturbances Along the Trans-Alaska Pipeline, 1975-1978. CRREL Report 81-12. Prepared for Office of the Chief of Engineers, by U.S. Army, Corps of Engineers, Cold Regions Research and Engineering Laboratory. 115 pp.

Johnson, P.R., and C.M. Collins. 1980. Snow Pads Used for Pipeline Construction in Alaska, 1976: Construction, Use and Breakup. CRREL Report 80-17. Prepared for Directorate of Military Programs, Office of the Chief of Engineers, by U.S. Army, Corps of Engineers, Cold Regions Research and Engineering Laboratory.

Johnson, S.R. 2000. Lesser snow geese. Pp. 233-257 in The Natural History of An Arctic Oil Field, J.C. Truett, and S.R. Johnson, eds. San Diego: Academic Press.

Johnson, S.R. 2000. Pacific eider. Pp. 259-275 in in The Natural History of An Arctic Oil Field, J.C. Truett, and S.R. Johnson, eds. San Diego: Academic Press.

Jones, H.G., J.W. Pomeroy, D.A. Walker, and R.W. Hoham. 2001. Snow Ecology: An Interdisciplinary Examination of Snow-Covered Ecosystems. Cambridge: Cambridge University Press. 378 pp.

Jorgenson, J.C., B.E. Reitz, et al. 1996. Tundra Disturbance Recovery Nine Years After Winter Seismic Exploration in Northern Alaska. Arctic National Wildlife Refuge Report. Fairbanks, AK: US Fish and Wildlife Service. 9pp.

Jorgenson, M.T. 1997. Patterns and rates of, and factors affecting natural recovery on land disturbed by oil development in arctic Alaska. Pp. 421-442 in Disturbance and Recovery in Arctic Lands: An Ecological Perspective, R.M.M. Crawford, ed. Dordrecht: Kluwer.

Jorgenson, M.T., and M.R. Joyce. 1994. Six strategies for rehabilitating land disturbed by oil development in arctic Alaska. Arctic 47(4):374-390.

Jorgenson, M.T., and J.E. Roth. 2001. Reconnaissance Survey and Monitoring of Seismic Trail Impacts on the Colville River Delta, 1997-1998. Prepared for Phillips Alaska Inc., Anchorage, AK, by ABR, Inc., Fairbanks, AK. 41pp.

Jorgenson, M.T., M.A. Robus, C.O. Zachel, and B.E. Lawhead. 1987. Effects of a Brine Spill on Tundra Vegetation and Soil in the Kuparuk Oilfield, Alaska. Final Report. Prepared for ARCO Alaska, Inc., and Kuparuk River Unit by Alaska Biological Research, Fairbanks, AK.

Jorgenson, M.T., K. Kielland, B.S. Schepart, and J.B. Hyzy. 1991. Bioremediation and Tundra Restoration After a Crude Oil-Spill Near Drill Site 2U, Kuparuk Oilfield, Alaska, 1990. Prepared for ARCO Alaska, Inc. and the Prudhoe Bay Unit, by Alaska Biological Research, Inc., Fairbanks, and Waste Stream Technology Inc., Buffalo, NY.

Jorgenson, M.T., B.E. Lawhead, and C.B. Johnson. 1997a. Integrated studies of geomorphology, landscape ecology, and wildlife for environmental impact analysis of a proposed oil devlopment project in arctic Alaska. Pp. 365-368 in ISCORD'97:

Proceedings of the Fifth International Symposium on Cold Region Development, May 4-10, 1997, Anchorage, AK, H.K. Zubeck, C.R. Woolward, D.M. White, and T.S. Vinson, eds. Hanover, NH: Cold Regions Research and Engineering Laboratory.

Jorgenson, M.T., J.E. Roth, E.R. Pullman, R.M. Burgess, M.K. Raynolds, A.A. Stickney, M.D. Smith, and T.M. Zimmer. 1997b. An Ecological Land Survey for the Colville River Delta, Alaska, 1996. Final Report. Fairbanks, AK: ABR, Inc.

Joyce, M.R., L.A. Rundquist, L.L. Moulton, R.W. Firth, and E.H. Follmann. 1980. Gravel Removal Guidelines Manual for Arctic and Subarctic Floodplains. FWS/OBS-80/09. Washington, DC: U.S. Dept of the Interior, Fish and Wildlife Service.

Kadlec, J.A., and W.H. Drury. 1968. Structure of the New England herring gull population. Ecology 49(4):644-676.

Kawagley, A.O. No date. Yupiaq Education Revisited [Online]. Available: http://arcticcircle.uconn.edu/HistoryCulture/kawagley.html [accessed Dec. 11, 2002].

Kaye, R. 2000. The Arctic National Wildlife Refuge: An exploration of the meanings embodied in America's Last Great Wilderness. Pp. 73-80 in in Wilderness Science in a Time of Change Conference, Vol. 2. Wilderness Within the Context of Larger Systems, S.F. McCool, D.N. Cole, W.T. Borrie, J. O'Loughlin, comps. Proceedings RMRS-P-15-Vol-2. Ogden, UT: Department of Agriculture, Forest Service, Rocky Mountain Research Station [Online]. Available: http://www.wilderness.net/research.cfm [accessed Dec. 11, 2002].

Kelley, J., and G. Laursen, eds. 1980. Investigation of the Occurrence and Behavior Patterns of Whales in the Vicinity of the Beaufort Sea Lease Area, Final Report for the Period October 1, 1978 through November 30, 1979. Prepared for U.S. Dept. of the Interior, Bureau of Land Management, Alaska OCS Office, by the Naval Arctic Research Laboratory, Barrow, Alaska. 753 pp.

Kelly, B.P., J.J. Burns, and L.T. Quakenbush. 1988. Responses of ringed seals (*Phoca hispida*) to noise disturbance. Pp. 27-38 in Port and Ocean Engineering Under Arctic Conditions, Vol. 2., W.M. Sackinger, and M.O. Jeffries, eds. Fairbanks, AK: Geophysical Institute, University of Alaska.

Kenney, R.M., M.C. Garcia, and J.I. Everitt. 1981. The biology of the reproductive and endocrine systems of the bowhead whale, *Balaena mysticetus*, as determined by evaluation of tissues and fluids from subsistence-killed whales (RU 580). Pp. 89-115 in Tissue Structural Studies and Other Investigations on the Biology of Endangered Whales in the Beaufort Sea. Final Report for the period April 1, 1980 through June 30, 1981, Vol. 1., T.F. Albert, ed. Prepared for U.S. Dept. of the Interior, Bureau of Land Management, Alaska OCS Office, by Dept. of Veterinary Science, University of Maryland, College Park, MD.

Kertell, K. 1996. Response of pacific loons (*Gavia pacifica*) to impoundments at Prudhoe Bay, Alaska. Arctic 49(4):356-366.

Kertell, K. 2000. Pacific loon. Pp. 181-195 in The Natural History of An Arctic Oil Field, J.C. Truett, and S.R. Johnson, eds. San Diego: Academic Press.

Kertell, K., and R.L. Howard. 1997. Impoundment productivity in the Prudhoe Bay Oil Field, Alaska: Implications for waterbirds. Environ. Manage. 21(5):779-792.

King, J.G. 1970. The swans and geese of Alaska's Arctic Slope. Wildfowl 21:11-17.

Kinney, T.C., B.W. Santana, D.M. Hawkins, E.L. Long, and E. Yarmak Jr. 1983. Foundation stabilization of central gas injection facilities, Prudhoe Bay, Alaska. Pp. 618-622 in

Permafrost Fourth International Conference Proceedings. Washington, DC: National Academy Press.

Klein, D.R. 1970. Tundra ranges north of the boreal forest. J. Range Manage. 23:8-14.

Klein, D.R. 1973. The impact of oil development in northern environment. Pp. 109-121 in Petrolio e ambiente, Proceedings of 3rd Interpetrol Congress, April 11-14, 1973, Rome, Italy.

Klein, D.R. 1999. The roles of climate and insularity in establishment and persistence of *Rangifer tarandus* populations in the high Arctic. Ecol. Bull. 47:96-104.

Klinger, L.F., D.A. Walker, and P.J. Weber. 1983a. The effects of gravel roads on Alaskan arctic coastal plain tundra. Pp. 628-633 in Permafrost Fourth International Conference Proceedings. Washington, DC: National Academy Press.

Klinger, L.F., D.A. Walker, M.D. Walker, et al. 1983b. The Effects of a Gravel Road on Adjacent Tundra Vegetation: Prudhoe Bay Waterflood Environmental Monitoring Program. Boulder, CO: Institute of Arctic and Alpine Research, University of Colorado. 166 pp.

Ko, D., and J.E. Zeh. 1988. Detection of migration using sound location. Biometrics 44(3):751-763.

Kofinas, G. with the communities of Aklavik, Arctic Village, Old Crow, and Fort McPherson. 2002. Community contributions to ecological monitoring: Knowledge co-production in the U.S.-Canada Arctic borderlands. Pp. 55-91 in The Earth is Faster Now: Indigenous Observations of Arctic Environmental Change, I. Krupnik, and D. Jolly, eds. Fairbanks, AK: Arctic Research Consortium of the United States.

Kohut, R.J., J.A. Laurence, P. King, R. Raba, and A.J. Belsky. 1994. Assessment of the Effects of Air Quality on Arctic Tundra Vegetation at Prudhoe Bay, Alaska. Final Report. Prepared by Boyce Thompson Institute for Plant Research, Cornell University, Ithaca, NY, for Alaska Oil and Gas Association, Anchorage, AK, and Alaska Science and Technology Foundation, Anchorage, AK.

Kornbrath, R.W., M.D. Myers, D.L. Krouskop, J.F. Meyer, J.A. Houle, T.J. Ryherd, and K.N. Richter. 1997. Petroleum Potential of the Eastern National Petroleum Reserve-Alaska. Division of Oil and Gas, Department of Natural Resources, State of Alaska. April 1997. 30 pp.

Koski, W.R., R.A. Davis, G.W. Miller, and D.E. Withrow. 1993. Reproduction. Pp. 239 -274 in The Bowhead Whale, J.J. Burns, J.J. Montague, and C.J. Cowles, eds. Special Publ. No. 2. Lawrence, KS: Society for Marine Mammalogy.

Kral, S. 1992. Red Dog: Cominco's Arctic experience pays off again. Mining Engineering 44(1):43-49.

Krannich, R.S., and S.L. Albrecht. 1995. Opportunity/threat responses to nuclear waste disposal facilities. Rural Sociol. 60(3):435-453.

Krupnik, S. 1987. The bowhead vs. the gray whale in Chukotkan aboriginal whaling. Arctic 40(1):16-32.

Kruse, J.A., J. Kleinfeld, and R. Travis. 1982. Energy development on Alaska's North Slope: Effects on the Inupiat population. Hum. Organ. 41:97-106.

Kruse, J.A., M. Baring-Gould, W. Schneider, J. Gross, G. Knapp, and G. Sherrod. 1983. A Description of the Socioeconomics of the North Slope Borough. Technical Report No 85. Prepared by Institute of Social and Economic Research, University of Alaska, for Minerals Management Service, Alaska Outer Continental Shelf Region, Anchorage, AK.

Kubanis, S.A. 1980. Recolonization by Native and Introduced Plant Species Along the Yukon River-Prudhoe Bay Haul Road, Alaska. M.S. Thesis. San Diego State University. 129pp.

Kulas, J.E. 1992. Geology of the Red Dog Mine, Western Brooks Range, Alaska. Preprint No. 92 –70. Society for Mining, Metallurgy and Exploration Inc., Littleton, CO. Prepared for presentation at the SME Annual Meeting, February 24-27, 1992, Phoenix, AZ.

Kuropat, P.J. 1984. Foraging Behavior of Caribou on a Calving Ground in Northwestern Alaska. M.S. Thesis. University of Alaska, Fairbanks. 95pp.

Kuropat, P.J., and J.P. Bryant. 1979. Foraging behavior of cow caribou on the Utukok calving grounds in Northwestern Alaska. Pp. 64-70 in Proceedings of the Second International Reindeer/Caribou Symposium, Sept.17-21,1979, Roros, Norway, Part A, E. Reimers, E. Gaare, and S. Skjenneberg, eds. Trondheim: Direktoratet for vilt og ferskvannsfisk.

Kvenvolden, K.A. 1993. A primer on gas hydrates. Pp. 279-291 in The Future of Energy Gases, D.G. Howell, ed. USGS Professional Paper 1570. Washington, DC: U.S. G.P.O.

LaBelle, R.P., and C.M. Anderson. 1985. The application of oceanography to oil-spill modeling for the Outer Continental Shelf Oil and Gas Leasing Program. Mar. Technol. Soc. J. 19(2):19-26.

Lachenbruch, A.H. 1957a. Thermal Effects of the Ocean on Permafrost. Pp. 1515-1529 in U.S. Geological Survey Bulletin. Geological Society of America. (Reprinted from the Bulletin of Geological Society of America, Vol. 68, Nov. 1967).

Lachenbruch, A.H. 1957b. Three-Dimensional Heat Conduction in Permafrost Beneath Heated Buildings. U.S. Geological Survey Bulletin 1052-B. Washington, DC: U.S. G.P.O.

Lachenbruch, A.H. 1959. Periodic Heat Flow in a Stratified Medium, With Application To Permafrost Problems. U.S. Geological Survey Bulletin 1083-A. Washington, DC: U.S. G.P.O. 36 pp.

Lachenbruch, A.H. 1962. Mechanics of Thermal Contraction Cracks and Ice-Wedge Polygons in Permafrost. Geological Society of America Special Paper No. 70. New York: Geological Society of America. 69 pp.

Lachenbruch, A.H. 1966. Contraction theory of ice wedge polygons: A qualitative discussion. Pp. 63-71 in Permafrost: First International Conference Proceedings, Nov. 11-15, 1963, Lafayette, Indiana. Pub. No.1287. Washington, DC: National Academy of Sciences.

Lachenbruch, A.H. 1970. Some Estimates of the Thermal Effects of a Heated Pipeline in Permafrost. Geological Survey Circular 632. Washington, DC: U.S. Geological Survey.

Lachenbruch, A.H. 1994. Permafrost, the Active Layer, and Changing Climate. Open-File Report 94-694. Menlo Park, CA : U.S. Geological Survey.

Lachenbruch, A.H. 2001. Permafrost. Pp. 224-235 in Encyclopedia of Global Change: Environmental Change and Human Society, Vol. 2., A.S. Goudie, ed. New York: Oxford University Press.

Lachenbruch, A.H., and B.V. Marshall. 1986. Changing climate: Geothermal evidence from permafrost in the Alaskan Arctic. Science 234(4777):689–696.

Lachenbruch, A.H., J.H. Sass, B.V. Marshall, and T.H. Moses Jr. 1982a. Permafrost, heat flow, and the geothermal regime at Prudhoe Bay, Alaska. J. Geophys. Res. 87:9301–9316.

Lachenbruch, A.H., J.H. Sass, L.A. Lawver, M.C. Brewer, B.V. Marshall, R.J. Munroe, J.P. Kennelly Jr., S.P. Galanis, Jr., and T.H. Moses Jr. 1982b. Temperature and depth of permafrost on the Arctic Slope of Alaska. Pp. 645–656 in Geology and Exploration of the National Petroleum Reserve in Alaska 1974-1982, G. Gryc, ed. U.S. Geological Survey Professional Paper 1399. Washington, DC: U.S. G.P.O.

Lachenbruch, A.H., T.T. Cladouhos, and R.W. Saltus. 1988. Permafrost temperature and the changing climate. Pp. 9–17 in Permafost: Fifth International Conference, Proceedings, August 2-5, 1988, Vol. 3, K. Sennesert, ed. Trondheim, Norway: Tapir.

Lambertsen, R.H., R.J. Hintz, W.C. Lancaster, A. Hirons, K. Kreiton, and C. Moor. 1989. Characterization of the Functional Morphology of the Mouth of the Bowhead Whale, *Balaena mysticetus*, with Special Emphasis on Feeding and Filtration Mechanisms. Philadelphia: Ecosystems, Inc. 134pp.

Lance, R. 2000. Industry Overview – "Doing it Right", The Alpine Development on Alaska's North Slope. Presented at Established Oil Technologies and Practices on Alaska's North Slope Workshop, April 2000, Anchorage, AK.

Landis, P. 1938. Three Iron Mining Towns, A Study in Cultural Change. Ann Arbor, MI: Edwards Brothers, Inc.

Lanctot, R.B., and C.D. Laredo. 1994. Buff-breasted sandpiper *Tryngites subruficollis*. No. 91 in The Birds of North America, Vol. 3., A. Poole, and F. Gill, eds. Philadelphia, PA: American Ornithologists' Union and The Academy of Natural Sciences of Philadelphia.

Lawhead, B.E. 1988. Distribution and movements of central Arctic herd caribou during the calving and insect seasons. Pp. 8-13 in Reproduction and Calf Survival: Proceedings of the 3rd North American Caribou Workshop, Chena Hot Springs, Alaska, Nov. 4-6, 1987, R.D. Cameron, J.L. Davis, and L.M. McManus, eds. Wildlife Technical Bulletin No. 8. Juneau, AK: Alaska Dept. Fish and Game.

Lawhead, B.E., L.C. Byrne, and C.B. Johnson. 1993. Caribou Synthesis, 1987-1990. 1990 Endicott Environmental Monitoring Program Final Report, Vol. 5. Prepared for Science Applications International Corp., Anchorage, AK. U.S. Army Corps of Engineers, Alaska District, Anchorage, AK.

Lawhead, B.E., A.K. Prichard, and M.D. Smith. 2002. Distribution of caribou calving in relation to weather conditions and oilfield infrastructure in the Kuparuk-Colville region of the Alaska North Slope. Proceedings of the 9th North American Caribou Workshop, Kuujjuaq, Quebec, April 23-27, 2001. In review. Unpublished.

Lawson, D.E. 1982. Long-Term Modifications of Perennially Frozen Sediment and Terrain at East Oumalik, Northern Alaska. CRREL 82-36. Hanover, NH: U.S. Army, Cold Regions Research and Engineering Laboratory.

Lawson, D.E., J. Brown, K.R. Everett, A.W. Johnson, V. Komárková, B.M. Murray, D.F. Murray, and P.J. Webber. 1978. Tundra Disturbances and Recovery Following the 1949 Exploratory Drilling, Fish Creek, Northern Alaska. CRREL Report 78-28. Prepared For U.S. Geological Survey, by Dept. of the Army, Cold Regions Research and Engineering Laboratory, Corps of Engineers, Hanover, NH.

Leffingwell, E. deK. 1919. The Canning River Region, Northern Alaska. U.S. Geological Survey Professional Paper 109. Washington, DC: Govt Print. Off.

Lenart EA. 2001. Units 26B and 26C Caribou Management Progress Report of Survey-Inventory Activities. Alaska Department of Fish and Game. Federal Aid in Wildlife Restoration. Grants W-27-4 and W-27-5. Study 3.0. Juneau, AK. In press.

Lentfer, J.W., ed. 1988. Selected Marine Mammals of Alaska: Species Accounts with Research and Management Recommendations. Washington, DC: U.S. Marine Mammal Commission. 275 pp.

Lenvik, D., O. Granefjell, and J. Tamnes. 1988. Selection strategy in domestic reindeer. 5. Pregnancy in domestic reindeer in Trondelag County, Norway. Norsk Landbruksforskning 2:151-161.

Lewbel, G.S., and B.J. Galloway. 1984. Transport and fate of spilled oil. Pp. 7-29 in Proceedings of Synthesis Meeting, The Barrow Arch Environment and Possible Consequences of Planned Offshore Oil and Gas Development, Girdwood, Alaska, 30 Oct.-1. Nov 1983, J.C. Truett, ed. Outer Continental Shelf Environmental Assessment Program, NOAA/ Ocean Assessments Division, Alaska Office, Anchorage. AK.

LGL Alaska Research Associates, Inc. 1990. The 1988 Endicott Development Fish Monitoring Program, Vol. 2. Recruitment and Population Studies, Analysis of Fyke Net Data. Prepared for BP Exploration (Alaska) Inc., and North Slope Borough, by LGL Alaska Research Associates, Inc., Anchorage, AK.

LGL Alaska Research Associates, Inc. 1991. The 1989 Endicott Development Fish Monitoring Program, Vol. 2. Analysis of Fyke Net Data. Prepared for BP Exploration (Alaska) Inc. and North Slope Borough, by LGL Alaska Research Associates, Inc., Anchorage, AK.

LGL Alaska Research Associates, Inc. 1992. The 1990 Endicott Development Fish Monitoring Program, Vol. 2 Recruitment and Population Studies, Analysis of Fyke Net Data. Prepared for BP Exploration (Alaska) Inc., and North Slope Borough, by LGL Alaska Research Associates, Inc., Anchorage, AK.

LGL Alaska Research Associates, Inc. 1993. The 1991 Endicott Development Fish Monitoring Program. Vol. 1. Analysis of Fyke Net Data. Prepared for BP Exploration (Alaska) Inc., and North Slope Borough, by LGL Alaska Research Associates, Inc., Anchorage, AK.

LGL Alaska Research Associates, Inc. 1994a. The 1992 Endicott Development Fish Monitoring Program. Vol. 1. Analysis of Fyke Net Data. Prepared for BP Exploration (Alaska) Inc., Anchorage, AK, and North Slope Borough, Barrow, AK, by LGL Alaska Research Associates, Inc., Anchorage, AK.

LGL Alaska Research Associates, Inc. 1994b. The 1993 Endicott Development Fish Monitoring Program, Vol. 1. Fish and Hydrography Data Report. Prepared for BP Exploration (Alaska) Inc., and North Slope Borough, by LGL Alaska Research Associates, Inc., Anchorage, AK.

LGL Alaska Research Associates, Inc. 1996. The 1995 Endicott Development Fish Monitoring Program, Vol. 1. Fish and Hydrography Data Report. Prepared for BP Exploration (Alaska) Inc., Anchorage, AK, by LGL Alaska Research Associates, Inc., Anchorage, AK. 180pp.

LGL Limited/Greeneridge Sciences, Inc. 1987. Responses of Bowhead Whales to an Offshore Drilling Operation in the Alaskan Beaufort Sea, Autumn 1986. Report from LGL Limited, King City, Ontario Canada and Greeneridge Sciences, Inc., Santa Barbara, CA, for Shell Western E&P Inc., Anchorage, AK.

Lindstedt-Siva, J. 1992. Ecological effectiveness of response measures. Pp. 140-146 in MTS'92 Global Ocean Partnership, Proceedings. Washington, DC: Marine Technology Society.

Lindstedt-Siva, J. 1995. The need for experimental spills. Spill Sci. Technol. Bull. 1(2):97-100.

Lipkin, R., and D.F. Murray. 1997. Alaska Rare Plant Field Guide. Washington, DC: U.S. Dept. of Interior.

Liston, G.E. 1999. Interrelationships among snow distribution, snowmelt, and snow cover depletion: Implications for atmospheric, hydrologic, and ecologic modeling. J. Appl. Meteorol. 38(10):1474-1487.

Ljungblad, D. 1986. Observations On The Behavior Of Bowhead Whales (*Balaena mysticetus*) In The Presence of Operating Seismic Exploration Vessels In the Alaskan Beaufort Sea. Paper SC/38/PS1 presented to Scientific Committee of International Whaling Commission at its 1986 meeting. 78 pp.

Ljungblad, D.K., B. Würsig, S.L. Swartz, and J.M. Keene. 1985. Observations On The Behavior Of Bowhead Whales (*Balaena mysticetus*) In The Presence Of Operating Seismic Exploration Vessels in the Alaskan Beaufort Sea. Prepared to Minerals Management Service, Alaska OCS Region, from SEACO Inc., San Diego, CA. NTIS PB87-129318.

Ljungblad, D.K., B. Würsig, S.L. Swartz, and J.M. Keene. 1988. Observations on the behavioral responses of bowhead whales (*Balaena mysticetus*) to active geophysical vessels in the Alaskan Beaufort Sea. Arctic 41(3):183-194.

Loughlin, T.R. 1994. Marine Mammals and the *Exxon Valdez*. San Diego: Academic Press.

Lowry, L.L. 1993. Foods and feed ecology. Pp. 201-238 in The Bowhead Whale, J.J. Burns, J.J. Montague, and C.J. Cowles, eds. Special Publ. No. 2. Lawrence, KS: Society for Marine Mammalogy.

Lowry, L.F. 2000. Marine mammal-sea ice relationships. Pp. 91-96 in Impacts of Changes in Sea Ice and Other Environmental Parameters in the Arctic, H.P. Huntington, ed. Bethesda, MD: U. S. Marine Mammal Commission.

Lowry, L.F., and J.J. Burns. 1980. Foods utilized by bowhead whales near Barter Island, Alaska, autumn 1979. Mar. Fish. Rev. 42(9-10): 88-91.

Lowry, L.F., and K.J. Frost. 1984. Foods and feeding of bowhead whales in western and northern Alaska. Scientific Reports of the Whales Research Institute, Tokyo. 35: 1-16.

Lowry, L.F., K.J. Frost, and J.J. Burns. 1980. Variability in the diet of ringed seals, Phoca hispida, in Alaska. Can. J. Fish Aquat. Sci. 37(12):2254-2261.

Lowry, L.F., K.J. Frost, and K.W. Pitcher. 1994. Observations of oiling of harbor seals in Prince William Sound. Pp. 209-226 in Marine Mammals and the *Exxon Valdez*, T.R. Loughlin, ed. San Diego: Academic Press.

Lowry, L., G. Sheffield, and J.C. George. 2001. Bowhead whale feeding in the Alaskan Beaufort Sea. Abstract in Proceedings of the 14th Biennial Conference on the Biology of Marine Mammals, Nov. 28-Dec. 3, 2001, Vancouver, Canada.

Lunardini, V.J. 1981. Heat Transfer in Cold Climates. New York: Van Nostrand Reinhold Co.

Luton, H.H. 1986. Wainwright, Alaska: The Making of Inupiaq Cultural Continuity In A Time of Change. Ph.D. Dissertation. University of Michigan.

MacCarthy, G.R. 1953. Recent changes in the shoreline near Barrow, AK. Arctic 6(1):44-51.

Mackay, J.R. 1979. Pingos of the Tuktoyaktuk Peninsula area, Northwest Territories. Geographie Physique et Quaternaire. 33(1):3-61.

Maham, W. 2001. The Evolution of Waste Management on Alaska's North Slope. Presented at Interstate Oil and Gas Compact Commission, Midyear Meeting, May 15, 2001, Anchorage, AK.

Mallary, C.R. 1998. A Review of Alaska North Slop Blowouts, 1974-1997. Shared Services Drilling.

Mallek, E.J., and R.J. King. 2000. Aerial Breeding Pair Surveys of the Arctic Coastal Plain of Alaska-1999. Final Report. U.S. Dept. of the Interior, Fish and Wildlife Service, Fairbanks, AK.

Mangarella, P.A., J.R. Harper, and T.G. Weingartner. 1982. Prudhoe Bay Waterflood Physical Processes Monitoring, Program, 1981. Prepared for Department of the Army, Alaska District, Corps of Engineers, by Woodward-Clyde Consultants, Anchorage, AK.

Mapmakers Alaska. 2000. Arctic Slope and Beaufort Sea Alaska, Oil and Gas Activity Map. Mapmakers Alaska [Online]. Available: http://www.mapalaska.com/Products/Arctic_Slope/Arctic_Slope_Lease_Map/arctic_slope_lease_map.html [accessed Dec. 12, 2002].

Martin, L. 1986. Benthic infauna. Benthic epifauna. Pp. 110-136 in Review of the Biological Fate and Effects of Oil in Cold Marine Environments, W.S. Duval, ed. Report EE-74. Prepared by ESL Evironmental Services, Ltd., S.L. Ross Environmental Research, Ltd, and Arctic Laboratories, Ltd., for Environmental Protection Service, Environment Canada, Ottawa, Ontario.

Martin, L.R., and B.J. Gallaway. 1994. The effects of the Endicott Development Project on the Boulder Patch, an arctic kelp community in Stefansson Sound, Alaska. Arctic 47(1):54-64.

Martin, L.R., B.J. Gallaway, S.V. Schonberg, and K.H. Dunton. 1988. Photographic studies of the Boulder Patch epilithic community. Pp. 5-1 to 5-13 in Endicott Beaufort Sea Boulder Patch Monitoring Program (1986-1987), Annual Report, B.J. Gallaway, L.R. Martin, and K.H. Dunton, eds. Prepared by LGL Ecological Research Associates, Inc., Bryan, TX, for Standard Alaska Production Company, Anchorage, AK.

Mason, O.K., and S.C. Gerlach. 1995. Chukchi hot spots, paleo-polynyas and caribou crashes: Climatic and ecological dimensions of north Alaska prehistory. Arctic Anthropol. 32(1):101-130.

Maxim, L.D., and R.W. Niebo. 2001. Analysis of Spills Associated with Alaska North Slope (ANS) Exploration and Production (E&P) Activities. Draft. Prepared by Everest Consulting Associates, Cranbury, NJ, for TAPS Owners Alaska, Anchorage, AK. June 2001.

Maxim, L.D., and R.W. Niebo. 2001a. Water Spills on the Alaska North Slope. Prepared by Everest Consulting Associates, Cranbury, NJ, for Alaska Oil and Gas Association, Anchorage, AK. October 2001.

Maxim, L.D., and R.W. Niebo. 2001b. Appendix B. Oil Spill Analysis for North Slope Oil Production and Transportation Operations. Environmental Report for Trans Alaska Pipeline System Right-of-Way Renewal. Draft. Trans Alaska Pipeline System Owners [Online]. Available: http://tapseis.anl.gov/documents/report.cfm [accessed Dec. 11, 2002].

McAuliffe, C.D., B.L. Steelman, W.R. Leek, D.E. Fitzgerald, J.P. Ray, and C.D. Barker. 1981. The 1979 Southern California dispersant treated research oil spills. Pp. 269-282 in Proceedings: 1981 Oil Spill Conference (Prevention, Behavior, Control, Cleanup) March 2-5, 1981, Atlanta, GA. American Petroleum Institute Publ. No. 4334. Washington, DC: American Petroleum Institute.

McCourt, K.H., J.D. Feist, D. Doll, and J.J. Russell. 1974. Disturbance Studies of Caribou and Other Mammals in the Yukon and Alaska, 1972. Arctic Biological Report No. 5. Prepared by Renewable Resources Consulting Services Ltd, Edmonton. Calgary: Canadian Arctic Gas Study, Alaskan Arctic Gas Study Company. 246pp.

McHale, J.E. 1999. Alaska Clean Seas 1999 Annual Report. Alaska Clean Seas, Prudhoe Bay, AK.

McKendrick, J.E. 1987. Plant succession on disturbed sites, North Slope, Alaska, USA. Arct. Alp. Res. 19(4):554-565.

McKendrick, J.D. 1997. Long-term tundra recovery in northern Alaska. Pp. 503-518 in Disturbance and Recovery in Arctic Lands: An Ecological Perspective, R.M.M. Crawford, ed. Dordrecht: Kluwer.

McKendrick, J.D. 2000a. Alpine Pipeline Seawater Leak Effects on Surface Water, Soil, and Vegetation. Final Report. Prepared for Phillips Alaska, Inc., Anchorage, AK, by Lazy Mountain Research, Palmer, AK. November 20, 2000.

McKendrick, J.D. 2000b. Vegetative responses to disturbance. Pp. 35-56 in The Natural History of An Arctic Oil Field, J.C. Truett, and S.R. Johnson, eds. San Diego: Academic Press.

McKendrick, J.D. 2002. Soils and Vegetation of the Trans-Alaska Pipeline Route: A 1999 Survey. University of Alaska Fairbanks, School of Agriculture and Land Resources Management. Bulletin 109. University of Alaska Fairbanks, Fairbanks, AK.

McKendrick, J.D., and W.W. Mitchell. 1978. Effects of burning crude oil spilled onto six habitat types in Alaska. Arctic 31(3):277-295.

Meehan, R.H. 1986. Impact of Oilfield Development on Shorebirds, Prudhoe Bay, Alaska. Ph.D. Thesis. University of Colorado, Boulder, CO.

Melville, D.S. 1997. Threats to waders along the east Asian-Australasian flyway. Pp. 15-34 in Shorebird Conservation in the Asia-Pacific Region, P. Straw, ed. Hawthorn East, Australia: Australasian Wader Studies Group of Birds Australia.

Merritt, R.D., and C.C. Hawley. 1986. Map of Alaska's Coal Resources. Special Report 37. Fairbanks: Alaska Dept. of Natural Resources, Division of Mining and Geological and Geophysical Surveys.

Milkov, A.V., and R. Sassen. 2001. Structurally focused gas hydrate a future northwest U.S. Gulf resource. Offshore(Tulsa) 61(9):92-94.

Miller, D.R. 1976. Biology of the Kaminuriak Population of Barren-Ground Caribou. Part 3. Taiga Winter Range Relationships and Diet. Can. Wildl. Serv. Rep. Ser. No. 36. Ottawa: Environment Canada, Wildlife Service. 42pp.

Miller, D.S. 2001. Ground Zero. Amicus J. 23(2):29-32.

Miller, F.L., and A. Gunn. 1979. Inter-island movements of peary caribou (Rangifer tarandus pearyi) south of Viscount Melville Sound and Barrow Strait, Northwest Territories, Canada. Pp. 99-114 in Proceedings of the Second International Reindeer/Caribou Symposium, Sept. 17-21, 1979, Roros, Norway, Part A, E. Reimers, E. Gaare, and S. Skjenneberg, eds. Trondheim: Direktoratet for vilt og ferskvannsfisk.

Miller, F.L., E.J. Edmonds, and A. Gunn. 1982. Foraging Behavior of Peary Caribou in Response to Springtime Snow and Ice Conditions. Can. Wildl. Serv. Occasional Paper No. 48. Ottawa: Canadian Wildlife Service. 41pp.

Miller, M.C., V. Alexander, and R.J. Barsdate. 1978. The effects of oil spills on phytoplankton in an artic lake and ponds. Arctic 31(3):192-218.

Miller, M.C., R.T. Prentki, and R.J. Barsdate. 1980. Physics. Pp. 51-75 in Limnology of Tundra Ponds, Barrow, Alaska, J.E. Hobbie, ed. US/IBP Synthesis Series 13. Stroudsburg, PA: Dowden, Hutchinson and Ross.

Miller, M.W. 1994. Route selection to minimize helicopter disturbance of molting Pacific black brant: A simulation. Arctic 47(4):341-349.

Miller, M.W., K.C. Jensen, W.E. Grant, and M.W. Weller. 1994. A simulation model of helicopter disturbance of molting Pacific black brant., Ecol. Model. 73(3/4):293-309.

Mitchell, R., and R.T. Carson. 1989. Using Surveys to Value Public Goods: The Contingent Valuation Method. Washington, DC: Resources for the Future.

MMS (Minerals Management Service). 1987a. Alaska Outer Continental Shelf Chuckchi Sea Oil and Gas Lease Sale 109, Final Environmental Impact Statement, Vol. 1. MMS 87-0110. Anchorage: U.S. Dept. of the Interior, Minerals Management Service, Alaska OCS Region.

MMS (Minerals Management Service). 1987b. Beaufort Sea Sale 97. Alaska Outer Continental Shelf. Final Environmental Impact Statement, Vol.1. OCS EIS/EA, MMS 87-0069. PB88-118625/AS. Anchorage: U.S. Dept. of the Interior, Minerals Management Service.

MMS (Minerals Management Service). 1990a. Beaufort Sea Planning Area Oil and Gas Lease Sale 124. Final Environmental Impact Statement. OCS EIS/EA, MMS 90-0063. Anchorage: U.S. Dept. of the Interior, Minerals Management Service, Alaska OCS Region.

MMS (Minerals Management Service). 1990b. Chuckchi Sea Oil and Gas Lease Sale 126, Final Environmental Impact Statement, Vol. 1. MMS 90-0035. Anchorage: U.S. Dept. of the Interior, Minerals Management Service, Alaska OCS Region.

MMS (Minerals Management Service). 1991. Chukchi Sea Oil and Gas Lease Sale 126. Final Environmental Impact Statement. OCS EIS/EA, MMS 90-0095. Anchorage: U.S. Dept. of the Interior, Minerals Management Service, Alaska OCS Region.

MMS (Minerals Management Service). 1992. Area Evaluation and Decision Process. The Proposed Final Comprehensive Outer Continental Shelf Natural Gas and Oil Resources Management Program for 1992-1997. Herndon, VA: U.S. Department of the Interior, Minerals Management Service. April.

MMS (Minerals Management Service). 1996. Arctic Synthesis Meeting, October 23-25, 1995, Proceedings, K.L. Mitchell et al., eds. MMS 95-0065. NTIS PB97-105449. Prepared by MBC Applied Environmental Sciences, Inc., Costa Mesa, CA, for U.S. Dept. of the Interior, Mineral Management Service, Alaska Outer Continental Shelf Office, Anchorage, AK.

MMS (Minerals Management Service). 1997. Arctic Seismic Synthesis and Mitigating Measures Workshop, March 5-6, 1997, Barrow, AK, Proceedings, T. Newbury et al, eds. MMS 97-0014. PB98-132269. Prepared by MBC Applied Environmental Sciences, Inc., Costa Mesa, CA, for U.S. Dept. of the Interior, Mineral Management Service, Alaska Outer Continental Shelf Office, Anchorage, AK.

MMS (Minerals Management Service). 1997. Beaufort Sea Planning Area, Oil and Gas Lease Sale 170. Draft Environmental Impact Statement. MMS 97-0011. Anchorage: U.S. Dept. of the Interior, Minerals Management Service, Alaska OCS Region.

MMS (Minerals Management Service). 1998. Beaufort Sea Planning Area, Oil and Gas

Lease Sale 170. Final Environmental Impact Statement. MMS 98-0007. Anchorage: U.S. Dept. of the Interior, Minerals Management Service, Alaska OCS Region.

MMS (Minerals Management Service). 2000. Gulf of Mexico OCS Oil and Gas Lease Sales 181: Eastern Planning Area. Draft Environmental Impact Statement. MMS 2000-077. New Orleans: U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region.

MMS (Minerals Management Service). 2001a. Liberty Development and Production Plan, Draft Environmental Impact Statement, Vol. 1. OCS EIS/EA, MMS 2001-001. Department of the Interior, Minerals Management Service, Alaska OCS Region [Online]. Available: http://WWW.mms.gov/alaska/cproject/liberty [accessed Dec.11, 2002].

MMS (Minerals Management Service). 2001c. Active Lease Summary Table. List of Alaska Region Lease Sales. Minerals Management Services, Alaska OCS Region, U.S. Department of the Interior [Online]. Available: http://www.mms.gov/alaska/lease/hlease/leasetable.HTM [accessed Dec. 11, 2002].

MMS (Minerals Management Service). 2001b. Table V.B-3. In Liberty Development and Production Plan, Draft Environmental Impact Statement, Vol. 2. OCS EIS/EA, MMS 2001-001. Department of the Interior, Minerals Management Service, Alaska OCS Region [Online]. Available: http://WWW.mms.gov/alaska/cproject/liberty [accessed Dec.11, 2002].

Moiteret, C.S., T.R. Walker, and P.D. Martin. 1996. Predevelopment Surveys of Nesting Birds at Two Sites in the Kuparuk Oilfield, Alaska, 1988-1992. Tech. Report NAES-TR-96-02. U.S. Fish and Wildlife Service, Fairbanks, AK.

Monda, M.J. 1991. Reproductive Ecology of Tundra Swans on the Arctic National Wildlife Refuge, Alaska. Ph.D. Thesis. University of Idaho, Moscow, ID.

Monda, M.J., J.T. Ratti, and T.R. McCabe. 1994. Reproductive ecology of tundra swans on the Arctic National Wildlife Refuge, Alaska. J. Wildl. Manage. 58(4):757-773.

Montgomery Watson (Montgomery Watson Americas, Inc.). 1994. 1994 Kuparuk Environmental Studies. Seawater Treatment Plant NPDES Monitoring Report. Prepared for ARCO Alaska, Inc., and the Kuparuk River Unit, by Montgomery Watson Americas, Inc., Bellevue, WA. September 1994.

Moran, C.L. 2000. Spatial-Temporal Variation in Reproduction and Site Fidelity of Spectacled Eiders on the Yukon-Kuskokwim Delta, Alaska. M.S. Thesis. University of Alaska, Fairbanks, AK.

Morre, T.E., W.K. Wallace, K.J. Bird, S.M. Karl, C.G. Mull, and J.T. Dillon. 1994. Geology of northern Alaska. Pp. 49-140 in The Geology of Alaska, G. Plafker, and H.C. Berg, eds. The Geology of North America, Vol. G-1. Boulder, CO: Geological Society of America.

Morris, W.A. 2000. Seasonal Movements of Broad Whitefish (Coregonus nasus) in the Freshwater Systems of the Prudhoe Bay Oil Field. M.S. Thesis. University of Alaska, Fairbanks, AK. 71pp.

Mörschel, F.M., and D.R. Klein. 1997. Effects of weather and parasitic insects on behavior and group dynamics of caribou of the Delta Herd, Alaska. Can. J. Zool. 75(10):1659-1670.

Morton, P. 1999. The economic benefits of wilderness: Theory and practice. University of Denver Law Review 76(2):465-518.

Morton, P. 2000. Wildland economics: Theory and practice. Pp. 238-250 in Wilderness Science in a Time of Change Conference, Vol. 2. Wilderness Within the Context of Larger Systems, S.F. McCool, D.N. Cole, W.T. Borrie, J. O'Loughlin, comps. Proceedings RMRS-P-15-Vol-2. Ogden, UT: Department of Agriculture, Forest Service, Rocky Mountain Research Station [Online]. Available: http://www.wilderness.net/research.cfm [accessed Dec. 11, 2002].

Moulton, L.L. 1989. Recruitment of arctic cisco (*Coregonus autumnalis*) into the Colville delta, Alaska, in 1985. Pp. 107-111 in Research Advances on Anadromous Fish in Arctic Alaska and Canada, D.W. Norton, ed. Biological Papers of the University of Alaska 24. Fairbanks: Institute of Arctic Biology, University of Alaska.

Moulton, L.L. 1997. The 1996 Colville River Fishery. The 1997 Endicott Development Fish Monitoring Program, Vol. 2. Prepared by LGL Alaska Research Assoc., for BP Exploration (Alaska) Inc., Anchorage, and North Slope Borough, Barrow, AK.

Moulton, L.L. 2001. Harvest Estimate and Associated Information for the 2000 Colville River Fall Fishery. Prepared for Phillips Alaska, Inc., and BP Exploration (Alaska) Inc. Lopez Island, WA: MJM Research.

Moulton, L.L., and M.H. Fawcett. 1984. Oliktok Point Fish Studies - 1983. Prepared by Woodward-Clyde Consultants, for Kuparuk River Unit, ARCO Alaska Inc., Anchorage, AK.

Moulton, L.L., and J.C. George. 2000. Freshwater fishes in the Arctic oil-field region and coastal plain of Alaska. Pp. 327-348 in The Natural History of An Arctic Oil Field, J.C. Truett, and S.R. Johnson, eds. San Diego: Academic Press.

Moulton, L.L., B. Gallaway, M. Fawcett, W. Griffiths, K. Critchlow, R. Fechhelm, D. Schmidt, and J. Baker. 1986. 1984 Central Beaufort Sea fish study. Pp. 1-300 in Prudhoe Bay Waterflood Project Environmental Monitoring Program, 1984, Vol. 2. Final Report of Woodward-Clyde Consultants, Entrix, Inc., and LGL Ecological Research Associates, to U.S. Army Corps of Engineers, Anchorage, AK.

Muller, S.V., A.E. Racoviteanu, and D.A. Walker. 1999. Landsat MSS-derived land-cover map of northern Alaska: Extrapolation methods and a comparison with photo-interpreted and AVHRR-derived maps. Int. J. Remote Sens. 20(15):2921-2946.

Murdoch, J. 1892. Ethnological results of the Point Barrow expedition. In 9th Annual Report of the Bureau of American Ethnology for the Years 1887-1888, Washington, DC. Reprinted by Smithsonian Institution Press, Washington, DC.

Murphy, S.M. 1988. Caribou behavior and movements in the Kuparuk oil field: Implications for energetic and impact analyses. Pp. 196-210 in Reproduction and Calf Survival: Proceedings of the 3rd North American Caribou Workshop, Nov. 4-6, 1987, Chena Hot Springs, AK, R.D. Cameron, J.L. Davis, and L.M. McManus, eds. Wildlife Technical Bulletin No. 8. Juneau, AK: Alaska Dept. Fish and Game.

Murphy, S.M., and B.A. Anderson. 1993. Lisburne Terrestrial Monitoring Program: The Effects of the Lisburne Development Project on Geese and Swans, 1985-1989. Fairbanks, AK: Alaska Biological Research.

Murphy, S.M., and J.A. Curatolo. 1987. Activity budgets and movement rates of caribou encountering pipelines, roads, and traffic in northern Alaska. Can. J. Zool. 65:2483-2490.

Murphy, S.M., and B.E. Lawhead. 2000. Caribou. Pp. 59-84 in The Natural History of An Arctic Oil Field, J.C. Truett, and S.R. Johnson, eds. San Diego: Academic Press.

Murphy, S.M., D.E. Russell, and R.G. White. 2000. Modeling energetic and demographic consequences of caribou interactions with oil development in the Arctic. Pp. 107-110 in Proceedings of the 8th North American Caribou Workshop, Whitehorse, Yukon, Canada, April 20-24, 1998, R. Farnell, D. Russell, and D. van de Wetering, eds. Rangifer Spec. Issue 12. Tromso, Norway: Nordic Council for Reindeer Research.

Myers, K.C., and M.H. Barker. 1984. Examination of Drilling Reserve Pit Fluids and Effects of Tundra Disposal at Prudhoe Bay, Alaska, 1982-1983. Prepared for ARCO Alaska, Inc., Anchorage, AK. 109 pp.

Nadelhoffer, K.J., A.E. Giblin, G.R. Shaver, and A.E. Linkins. 1992. Microbial processes and plant nutrient availability in arctic soils. Pp. 281-300 in Arctic Ecosystems in a Changing Climate: An Ecophysiological Perspective, F.S. Chapin III, R.L. Jefferies, J.F. Reynolds, G.R. Shaver, J. Svoboda, and E.W. Chu, eds. San Diego: Academic Press.

Nageak, B.P., C.D. Brower, and S.L. Schliebe. 1991. Polar bear management in the southern Beaufort Sea: An agreement between the Inuvialuit Game Council and the North Slope Borough Fish and Game Committee. Trans. North Am. Wildl. Nat. Resour. Conf. 56:337-343.

NAST (National Assessment Synthesis Team). 2001. Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change. Cambridge: Cambridge University Press. 612pp.

Nellemann, C., and R.D. Cameron. 1996. Effects of petroleum development on terrain preferences of calving caribou. Arctic 49(1):23-28.

Nellemann, C., and R.D. Cameron. 1998. Cumulative impacts of an evolving oil-field complex on the distribution of calving caribou. Can. J. Zool. 76(8):1425-1430.

Nelson, K. 2002. Bidding to win. Petroleum News Alaska 7(23):1, 19-20. June 9, 2002.

Nelson, W.G., and A.A. Allen. 1982. The physical interaction and cleanup of crude oil with slush and solid first year sea ice. Pp. 37-59 in Proceedings of the Fifth Arctic Marine Oilspill Program Technical Seminar, June 15-17, 1982, Edmonton, Alberta. Ottawa: Research and Development Division, Environmental Emergency Branch, Environmental Protection Service.

Niebauer, H.J. 1991. Bio-physical oceanographic interactions at the edge of the Arctic ice pack. J. Mar. Syst. 2:209-232.

Niebo, R. 2001. Reconciliation of the TAPS ROW Database. Memorandum to R. Jakubezak, BP Pipelines, M. Radonich, BP Pipelines, and C. Loggie, Exxon, from R.Niebo, Everest Consalting Associates. April 30, 2001.

Niedoroda, A.W., and J.M. Colonell. 1990. Beaufort Sea causeways and coastal ocean dynamics. Pp. 509-516 in Proceedings of the 9th International Conference of Offshore Mechanics and Arctic Engineering 1990, Vol. 1. Offshore Technology, Part B, S.K. Chakrabarti, H. Maeda, C. Aage, and F.G. Neilsen, eds. New York, NY: American Society of Mechanical Engineers.

Nixon, J.F. 1986. Thermal simulation of subsea saline permafrost. Can. J. Earth Sci. 23(12):2039-2046.

Nixon, W.A.C. 1990. Group Dynamics and Behavior of the Porcupine Caribou Herd During the Insect Season. M.S. Thesis. University of Alaska, Fairbanks. 109pp.

NMFS (National Marine Fisheries Service). 2002. Biological Opinion, Endangered Species Act-Section 7 Consultation and Operation of the Liberty Oil Production Island.

Consultation No. F/AKR/2001/00889. National Marine Fisheries Service, Anchorage, AK. 51pp [Online]. Available: http://www.fakr.noaa.gov/protectedresources/whales/bowhead/biop.pdf [accessed Dec. 11, 2002].

NOCD (Naval Oceanography Command Detachment). 1986. Guide to Standard Weather Summaries and Climate Services. NAVAIR 50-IC-534. Asheville, NC: NOCD.

Noel, L.E., and R.H. Pollard. 1996. Yukon Gold Ice Pad Tundra Vegetation Assessment: 1993 Through 1995. Final report. Prepared by LGL Alaska Research Associates, Inc., for BP Exploration (Alaska) Inc., Anchorage, AK.

Noel, L.E., R.H. Pollard, W.B. Ballard, and M.A. Cronin. 1998. Activity and use of active gravel pads and tundra by caribou, *Rangifer tarandus granti*, within the Prudhoe Bay Oil Field, Alaska. Can. Field Nat. 112(3):400-409.

NORCOR Engineering and Research Ltd. 1975. The Interaction of Crude Oil With Arctic Sea Ice. Beaufort Sea Technical Report No. 27. Yellowknife, N.W.T.: NORCOR Engineering and Research Ltd.

Norris, M.A., K.R. Ptak, B.A. Zamora, and J.D. Hart. 2000. Implementation of tuned vibration absorbers for above ground pipeline vibration control. Pp. 115-121 in Proceedings of the 2000 International Pipeline Conference, Vol. 1., J.R. Ellwood, ed. New York: American Society of Mechanical Engineers.

Norton, D., and G. Weller. 1984. The Beaufort Sea: Background, history, and perspective. Pp. 3-19 in The Alaskan Beaufort Sea: Ecosystems and Environments, P.W. Barnes, D.M. Schell, and E. Reimnitz, eds. Orlando: Academic Press.

NRC (National Research Council). 1986. Ecological Knowledge and Environmental Problem-Solving: Concepts and Case Studies. Washington, DC: National Academy Press.

NRC (National Research Council). 1989. Using Oil Spill Dispersants On the Sea. Washington, DC: National Academy Press.

NRC (National Research Council). 1994. Environmental Information for Outer Continental Shelf Oil and Gas Decisions in Alaska. Washington, DC: National Academy Press.

NRC (National Research Council). 1995. Science and the Endangered Species Act. Washington, DC: National Academy Press.

NRC (National Research Council). 2003. Oil in the Sea III: Inputs, Fates, and Effects. Washington, DC: National Academies Press.

NSB (North Slope Borough). 1999. North Slope Borough: 1998/1999 Economic Profile and Census Report. Barrow, AK: Department of Planning and Community Services.

NSB (North Slope Borough). 2000. Comprehensive Annual Financial Report. North Slope Borough. Alaska.

NSB/SAC (North Slope Borough Scientific Advisory Committee). 1997. A Review of the 1996 Endicott Fish Monitoring Program Synthesis Reports. NSB-SAC-OR-135. North Slope Borough Scientific Advisory Committee, Barrow, AK. 33pp.

NWPS (National Wilderness Preservation System). 2002. Map of Central Alaska Wilderness Areas [Online]. Available: http://www.wilderness.net/nwps/maps/ak_map.cfm [accessed August 14, 2002].

Odum, W.E. 1982. Environmental degradation and the tyranny of small decisions. BioScience 32(9):728-729.

Oechel, W.C., and K. Van Cleve. 1986. The role of bryophytes in nutrient cycling in the taiga. Pp. 121-137 in Forest Ecosystems in the Alaskan Taiga: A Synthesis of Structure and

Function, K. Van Cleve, F.S. Chapin III, P.W. Flanagan, L.A. Vierek, and C.T. Dyrness, eds. Ecological Studies 37. New York: Springer-Verlag.

Oechel, W.C., G. Vourlitis, and S.J. Hastings. 1997. Cold-season CO_2 emission from arctic soils. Global Biogeochem. Cycles 11(2):163-172.

Olsson, P.Q., L.D. Hinzman, and M. Sturm, G.E. Liston, and D.L. Kane. 2002. Surface Climate and Snow-Weather Relationships of the the Kuparuk Basin on the Alaska's Arctic Slope. ERDC/CRREL TR-02-10. Hanover, NH: U.S. Army Crops Of Engineers, Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory.

Osterkamp, T.E. 1988. Permafrost temperature in the Arctic National Wildlife Refuge. Cold Reg. Sci. Technol. 15:191-193.

Osterkamp, T.E., and W.D. Harrison. 1982. Temperature Measurements in Subsea Permafrost off the Coast of Alaska. Ottawa: National Research Council of Canada.

Øritsland, N.A., F.R. Engelhardt, F.A. Juck, R.A. Hurst, and P.D. Watts. 1981. Effects of Crude Oil on Polar Bears. Environmental Studies No. 24. Ottawa: Northern Affairs Program, Department of Indian Affairs and Northern Development.

Ott, A.G. 1993. An Evaluation of the Effectiveness of Rehabilitation at Selected Streams in North Slope Oilfields. Tech. Report No. 93-5. Juneau, AK: Alaska Dept of Fish and Game Habitat and Restoration Division.

Overland, J.E., and A.T. Roach. 1987. Northward flow in the Bering and Chukchi seas. J. Geophys. Res. 92(C7):7097-7105.

Pamplin, W.L. 1979. Construction-Related Impacts of the Trans-Alaska Pipeline System on Terrestrial Wildlife Habitats. Special Repot No. 24. Joint State/Federal Fish and Wildlife Advisory Team, Anchorage, AK.

Parametrix, Inc. 1997. Alpine Development Project: Environmental Evaluation Document. Prepared for the U.S. Army Corps of Engineers, Anchorage, AK, by Parametrix, Inc., Kirkland, WA.

Pastor, J., R.J. Naiman, and B. Dewey. 1988. Moose, microbes, and the boreal forest; through selective browsing, moose change plant communities and ecosystem properties. Bioscience 38(11):770-777.

Patterson, A. 1974. Subsistence Harvests in Five Native Regions. Joint Federal-State Land Use Planning Commission for Alaska. Anchorage, AK: Resource Planning Team.

Pavlas, S.F., W.M. Fowler, S.J. Tonkins, and E.J. Young. 2000. ARCO uses vertical loops to contain potential oil line leaks. Pipeline and Gas Industry 83(6):53-57.

Pedersen, S., J. Taalak, and C. Utermohle. 2003. 1999-2000 Subsistence Harvest of Caribou and Other Big Game Resources in Nuiqsut, Alaska. Division of Subsistence- Arctic Region, Alaska Department of Fish and Game, Fairbanks, AK. In press.

Perkins, T.K., J.A. Rochon, R.A. Ruedrich, F.J. Schuh, and G.R. Wooley. 1975. Prudhoe Bay Field Permafrost Casing and Well Design for Thaw Subsidence Protection. Atlantic Richfield Company, North American Producing Division.

Petersen, M.R. 1979. Nesting ecology of arctic loons. Wilson Bull. 91:608-617.

Peterson, J. 2002a. Status Report. ADEC Reserve Pit Closure Program, January 18, 2002. Compiled by Judd Perterson, ADEC Reserve Pit Closure.

Peterson, K.M., and W.D. Billings. 1980. Tundra vegetational patterns and succession in relation to microtopography near Atkasook, Alaska. Arct. Alp. Res. 12:473-482.

Peterson, R.A., and W.B. Krantz. 1998. A linear stability analysis for the inception of differential frost heave. Pp. 883-889 in Proceedings of the 7th International Conference on Permafrost, June 23-27, 1998, Yellowknife, Canada, A.G. Lewkowicz, and M. Allard, eds. Quebec: Université Laval.

Petroleum News Alaska. 2001. Phillips and Anadarko announce five discovery wells in NPR-A. Petroleum News Alaska, News Bulletin 7(60-1). May 21, 2001.

Petroleum News Alaska. 2002a. State studies road to NPR-A. Petroleum News Alaska News Bulletin 8(99). September 24, 2002.

Petroleum News Alaska. 2002b. A portable exploration solution. Petroleum News Alaska 7(43). October 27, 2002.

Phillips (Phillips Petroleum Company). 2000. Building the New Phillips, Annual Report, 2000 [Online]. Available: http://www.phillips66.com/annual00/annual00pdf.htm [accessed September 16, 2002].

Pitelka, F.A., R.T. Homes, and S.F. MacLean, Jr. 1974. Ecology and evolution of social organization in arctic sandpipers. Am. Zool. 14:185-204.

Policansky, D. 2002. Catch-and-release recreational fishing: A historical perspective. Pp. 74-94 in Recreational Fisheries: Ecological, Economic, and Social Evaluation, T. Pitcher, and C. Hollingworth, eds. Oxford, UK: Blackwell Science.

Pollard, R.H., W.B. Ballard, L.E. Noel, and M.A. Cronin. 1996b. Parasitic insect abundance and microclimate of gravel pads and tundra. Can. Field-Nat. 110(4):649-658.

Pollard, R.H., W.B. Ballard, L.E. Noel, and M.A. Cronin. 1996a. Summer distribution of caribou, *Rangifer tarandus granti*, in the area of the Prudhoe Bay oil field, Alaska, 1990-1994. Can. Field-Nat. 110(4):659-674.

Pomeroy, J.W., and E. Brun. 2001. Physical properties of snow. Pp. 45-126 in Snow Ecology: An Interdisciplinary Examination of Snow-covered Ecosystems, H.G. Jones, J.W. Pomeroy, D.A. Walker, and R.W. Hoham, eds. Cambridge: Cambridge University Press.

Power, G. 1997. A review of fish ecology in Arctic North America. Pp. 13-39 in Fish Ecology in Arctic North America, J.B. Reynolds, ed. American Fisheries Society Symposium 19. Bethesda, MD: American Fisheries Society.

Portney, P.R. 1994. The contingent valuation debate: Why economics should care. J. Econ. Perspect. 8(4):3-18.

Pulliam, H.R. 1988. Sources, sinks, and population regulation. Am. Nat. 132(5):652-661.

Quinlan, S.E., and W.A. Lehnhausen. 1982. Arctic fox, *Alopex lagopus*, predation on nesting common eiders, *Somateria mollissma*, at Icy Cape, Alaska. Can. Field Nat. 96:462-466.

Radforth, J.R. 1972. Analysis of Disturbance Effects of Operations of Off-Road Vehicles on Tundra. ALUR Report 71-72-13. Northern Economic Development Branch, Department of Indian Affairs and Northern Development, Ottawa.

Raftery, A., and J. Zeh. 1998. Estimating bowhead whale population size and rate of increase from the 1993 census. J. Am. Stat. Assoc. 93(442):451-463.

Rausch, R.L. 1953. On the status of some arctic mammals. Arctic 6:91-148.

Raynolds, M.K., and N.A. Felix. 1989. Airphoto analysis of winter seismic disturbance in northeastern Alaska. Arctic 42(4):362-367.

Reed, J.C. 1958. Exploration of Naval Petroleum Reserve No. 4 and Adjacent Areas, Northern Alaska, 1944-1953. U.S. Geological Survey Professional Paper 301. Washington, DC: U.S. G.P.O.

Reimers, E. 1983. Reproduction in wild reindeer in Norway. Can. J. Zool. 61(1): 211-217.

Reimers, E. 2002. Calving time and foetus growth among wild reindeer in Norway. Rangifer 22(1):61-66.

Reimnitz, E., and E.W. Kempema. 1984. Pack ice interaction with stamukhi shoal Beaufort Sea, Alaska. Pp. 159-183 in The Alaskan Beaufort Sea: Ecosystems and Environments, P.W. Barnes, D.M. Schell, and E. Reimnitz, eds. Orlando: Academic Press.

Reimnitz, E., S.M. Graves, and P.W. Barnes. 1985. Beaufort Sea Coastal Erosion, Shoreline Evolution, and Sediment Flux. Open-File Report 85-380. Reston, VA: U.S. Dept. of the Interior, Geological Survey.

Revkin, A.C. 2001. Hunting for oil; New precision, less pollution. New York Times. Section F, Page 1. January 30, 2001.

Rex, R.W. 1961. Hydrodynamaic analysis of circulation and orientation of lakes in northern Alaska. Pp. 1021-1043 in Geology of the Arctic, Proceedings from the First International Symposium on Arctic Geology, January 11-13, 1960, Calgary, Vol. 2., G.O. Raasch, ed. Toronto: University of Toronto Press.

Reynolds, H.V. 1979. Population biology, movements, distribution, and habitat utilization of a grizzly bear population in NPR-A. Pp. 129-182 in Studies of Selected Wildlife and Fish and Their Use of Habitats on and Adjacent to National Petroleum Reserve in Alaska, 1977-1978, Vol.1, P.C. Lent, ed. Anchorage, AK: U.S. Department of Interior, National Petroleum Reserve in Alaska 105(c) Land Use Stady.

Richardson, W.J., ed. 1986. Importance of the Eastern Alaskan Beaufort Sea to Feeding Bowhead Whales, 1985. MMS 86-0026. Reston, VA: U.S. Minerals Management Service.

Richardson, W.J., ed. 1997. Northstar Marine Mammal Monitoring Program, 1996: Marine Mammal and Acoustical Monitoring of a Seismic Program in the Alaskan Beaufort Sea. LGL Report TA2121-2. Prepared by LGL Ltd., King City, Ontario, and Greeneridge Sciences, Inc., Santa Barbara, CA, for BP Exploration (Alaska) Inc., Anchorage, AK, and National Marine Fisheries Service,Anchorage, AK, and Silver Spring, MD. 245 pp.

Richardson, W.J., ed. 1998. Marine Mammal and Acoustical Monitoring of BPXA's Seismic Program in the Alaskan Beaufort Sea, 1997. Prepared by LGL Ltd., King City, Ontario, and Greeneridge Sciences Inc., Santa Barbara, CA, for BP Exploration (Alaska) Inc., Anchorage, AK, and National Marine Fisheries Service, Anchorage, AK, and Silver Spring, MD. 318pp.

Richardson, W.J., ed. 1999. Marine Mammal and Acoustical Monitoring of Western Geophysical's Open-Water Seismic Program in the Alaskan Beaufort Sea, 1998. LGL Report 2230-3. Prepared by LGL Ltd., King City, Ontario, and Greeneridge Sciences Inc., Santa Barbara, CA, for Western Geophysical, Houston, TX, and National Marine Fisheries Service, Anchorage, AK, and Silver Spring, MD. 390 pp.

Richardson, W.J., and M.T. Williams, eds. 2000. Monitoring of Ringed Seals During Construction of Ice Roads for BP's Northstar Oil Development, Alaskan Beaufort Sea, 1999. Prepared by LGL Ltd., King City, Ontario, and LGL Alaska Research Associates, Inc., Anchorage, AK, for BP Exploration (Alaska) Inc., Anchorage, AK, and National Marine Fisheries Service, Anchorage, AK, and Silver Spring, MD. 113pp.

Richardson, W.J., C.R. Green, Jr., C.I. Malme, and D.H. Thomson. 1995. Marine Mammals and Noise. New York: Academic Press. 576 pp.

Ritchie, R.J. 1991. Effects of oil development on providing nesting opportunities for gyrfalcons and rough-legged hawks in northern Alaska. Condor 93(1):180-184.

Ritchie, R.J., and J.G. King. 2000. Tundra swans. Pp. 197-220 in The Natural History of An Arctic Oil Field, J.C. Truett, and S.R. Johnson, eds. San Diego: Academic Press.

Ritchie, R.J., and A.M. Wildman. 2000. Aerial Surveys of Cliff-Nesting Raptors in the National Petroleum Reserve-Alaska (NPR-A), 1999. Final Report. Prepared for Bureau of Land Management, Fairbanks, AK, by ABR, Inc., Fairbanks, AK. 47pp.

Roberts, S.B., G.D. Stricker, and R.H. Affolter. 1991. Stratigraphy and Chemical Analyses of Coal Beds in the Upper Cretaceous and Tertiary Sagavanirktok Formation, East-Central North Slope, Alaska. U.S. Geological Survey Coal Investigations Map C-139B. Reston, VA: U.S. Geological Survey.

Robertson, D.G., A.W. Brackney, M.A. Spindler, and J.W. Hupp. 1997. Distribution of autumn-staging lesser snow geese on the northeast coastal plain of Alaska. J. Field Ornithol. 68(1):124-134.

Robertson, S.B. 1989. Impacts of petroleum development in the Arctic. Science 245 (4919):764-765.

Robertson, S.B. 1991. Habitat versus populations: Approaches for assessing impacts on fish. Pp. 97-108 in Fisheries and Oil Development on the Continental Shelf, C.S. Benner, and R.W. Middleton, eds. American Fisheries Society Symposium 11. Bethesda, MD: American Fisheries Society.

Robertson, T.L., and E. DeCola. 2001. Joint Agency Evaluation of the Spring and Fall 2000 North Slope Broken Ice Exercises. Prepared by Alaska Department of Environmental Conservation, North Slope Borrough, Alaska Department of Natural Resources, Minerals Management Service, and U.S. Coast Guard, Anchorage, AK.

Robilliard, G.A., R.W. Smith, and J.M. Colonell. 1988. Prudhoe Bay Waterflood Project Benthic Infauna and Water Quality Components of the NPDES Monitoring Program. Final Report. Prepared for ARCO Alaska, and Prudhoe Bay Unit, Anchorage, AK, by Entrix, Inc., Environmental Sciences and Engineering, Inc., Anchorage, AK, and EcoAnalysis, Ojai, CA.

Roby, D.D. 1978. Behavioral Patterns of Barren-Ground Caribou of the Central Arctic Herd Adjacent to the Trans-Alaska Oil Pipeline. M.S. Thesis. University of Alaska, Fairbanks. 200pp.

Rognmo, A., K.A. Markussen, E. Jacobsen, H.J. Grav, and A.S. Blix. 1983. Effects of improved nutrition in pregnant reindeer on milk quality, calf birth weight, growth, and mortality. Rangifer 3(2):10-18.

Rosenzweig, M.L. 1981. A theory of habitat selection. Ecology 62(2):327-335.

Ross, B.D. 1988. Causeways in the Alaskan Beaufort Sea. EPA 910/0-88-218. Anchorage, AK: U.S. Environmental Protection Agency, Region 10, Alaska Operations Office.

Rothrock, D.A., Y.Yu, and G.A. Maykut. 1999. Thinning of the Arctic sea-ice cover. Geophys. Res. Lett. 26(23):3469-3472.

Rugh, D.J., G.W. Miller, D.E. Withrow, and W.R. Koski. 1992. Calving intervals of bowhead whales established through photographic identifications. J. Mammal. 73(3):487-490.

Russell, D.E. 1976. Computer Simulation of *Rangifer* Energetics. M.F. Thesis. University of British Columbia, Vancouver. 93pp.

Russell, D.E., and R.G. White. 2000. Surviving in the north – a conceptual model of reproductive strategies in arctic caribou [abstract]. Pp. 67-70 in Proceedings of the 8th North American Caribou Workshop, Whitehorse, Yukon, Canada, April 20-24, 1998, R.Farnell, D.Russell, and D. van de Wetering, eds. Rangifer Spec. Issue 12. Tromso, Norway: Nordic Council for Reindeer Research.

Russell, D.E., A.M. Martell, and W.A.C. Nixon. 1993. Range Ecology of the Porcupine Caribou Herd. Rangifer, Spec. Issue No. 8. Tromso, Norway: Nordic Council for Reindeer Research.

Russell, D.E., K.L. Gerhart, R.G. White, and D. van de Wetering. 1998. Detection of early pregnancy in caribou: Evidence for embryonic mortality. J. Wildl. Manage. 62(3):1066-1075.

Russell, D.E., R.D. Cameron, R.G. White, and K.L. Gerhart. 2000. Mechanisms of summer weight gain in northern caribou herds [abstract]. Pp. 148 in Proceedings of the 8th North American Caribou Workshop, Whitehorse, Yukon, Canada, April 20-24, 1998, R. Farnell, D.Russell, and D. van de Wetering, eds. Rangifer Spec. Issue 12. Tromso, Norway: Nordic Council for Reindeer Research.

Sable, E.G., and G.D. Stricker. 1987. Coal in the National Petroleum Reserve in Alaska (NPRA). Framework geology and resources. Pp. 195-215 in Alaskan North Slope Geology, Vol.1, I.L. Tailleur, and P. Weimer, eds. Special Pub. No. 50. Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, CA, and Alaska Geological Society Alaska, Anchorage, AK.

Savoie, M.A., and D.E. Wilson. 1983. 1982 Physical Processes Monitoring Program: Prudhoe Bay Waterflood Environmental Monitoring Program, 1982, Vol. 2. Prepared for Department of the Army, Alaska District, Corps of Engineers, by Kinnetic Laboratories Inc., Archorage, AK. May 1, 1983.

Savoie, M.A., and D.E. Wilson. 1986. Prudhoe Bay waterflood project physical oceanographic processes monitoring program for 1984. Pp. 2-1 to 2-155 in Prudhoe Bay Waterflood Project Environmental Monitoring Program, 1984, Vol. 1. Prepared for Department of the Army, Alaska District, Corps of Engineers, by Kinnetic Laboratories Inc., Archorage, AK.

Schell, D.M., and R.A. Horner. 1981. Primary production, zooplankton, and trophic dynamics of the Harrison Bay and Sale 71 area. Pp. 3-12 in Proceedings of a Synthesis Meeting: Beaufort Sea Sale 71 Synthesis Report, D.W. Norton, and W.M. Sackinger, eds. U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, Office of Marine Pollution Assessment, U.S. Dept. of the Interior, Bureau of Land Management, Juneau, AK. December 1981.

Schell, D.M., P.J. Zieman, D.M. Parrish, K.H. Dunton, and E.J. Brown. 1982. Foodweb and Nutrient Dynamics in Nearshore Alaska Beaufort Sea Waters. Cumulative Summary Report. Fairbanks, AK: Institute of Water Resources, University of Alaska. February 1982.

Schmidt, D.R., R.O. McMillan, and B.J. Gallaway. 1983. Nearshore Fish Survey in the Western Beaufort Sea: Harrison Bay to Elson Lagoon. Final Report. Prepared by LGL Ecological Research Associates. Inc. Fairbanks, AK, for NOAA/ OCSEAP Juneau Project Office, Juneau, AK.

Schmidt, D.R., W.B. Griffiths, D.K. Beaubien, and C.J. Herlugson. 1991. Movement of young-of-the-year arctic ciscoes across the Beaufort Sea coast, 1985-1988. Pp. 132-144 in Fisheries and Oil Development on the Continental Shelf, C.S. Benner, and R.W. Middleton, eds. American Fisheries Society Symposium 11. Bethesda, MD: American Fisheries Society.

Schindler, J.F. 1988. History of exploration in the National Petroleum Reserve in Alaska, with emphasis on the period from 1975-1982. Pp. 13-72 in Geology and Exploration of the National Petroleum Reserve in Alaska, 1974 to 1982, G. Gryc, ed. U. S. Geological Survey, Professional Paper 1399. Washington, DC: U.S. G.P.O.

Schrader, F.C., and W.J. Peters. 1904. A Reconnaissance in Northern Alaska, Across the Rocky Mountains, Along Koyukuk, John, Anaktuvuk, and Colville Rivers, and the Arctic Coast to Cape Lisburne, in 1901. U.S. Geological Survey Professional Paper 20. Washington, DC: G.P.O.

Schueck, L.S., and J.H. Marzluff. 1995. Influence of weather on conclusions about effects of human activities on raptors. J. Wildl. Manage. 59(4):674-682.

Schueck, L.S., J.H. Marzluff, and K. Steenhof. 2001. Influence of military activities on raptor abundance and behavior. Condor 103(3):606-615.

Sedinger, J.S., and A.A. Stickney. 2000. Black brant. Pp. 221-232 in The Natural History of An Arctic Oil Field, J.C. Truett, and S.R. Johnson, eds. San Diego: Academic Press.

Sedinger, J.S., C.J. Lensink, D.H. Ward, R.M. Anthony, M.L. Wege, and G.V. Byrd. 1993. Current status and recent dynamics of the black brant, Branta bernicle, breeding population. Wildfowl 44:49-59.

Sedinger, J.S., D.H. Ward, R.M. Anthony, D.V. Derksen, C.J. Lensink, K.S. Bollinger, and N.K. Dawe. 1994. Management of Pacific brant: Population structure and conservation issues. Trans. North Am.Wildl. Nat. Resour. Conf. 59:50-62.

Sedinger, J.S., M.P. Herzog, B.T. Person, M.T. Kirk, T. Obritchkewitch, P.P. Martin, and A.A. Stickney. 2001. Large-scale variation in growth of Black Brant goslings related to food availability. Auk 118(4):1088-1095.

Sedinger, J.S., N.D. Chelgren, M.S. Lindberg, T. Obritchkewitch, and M.T. Kirk, I. Martin, B.A. Anderson, and D.H. Ward. 2002. Life-history implications of large-scale spatial variation in adult survival of black brant (Branta bernicla nigricans). Auk 119(2):510-514.

Selkregg, L.L., et al. 1975. Alaska Regional Profiles: Arctic Region, Vol. 2. Anchorage, AK: Arctic Environmental Information and Data Center.

Serreze, M.C., J.E. Walsh, F.S. Chapin III, T. Osterkamp, M. Dyurgerov, V. Romanovsky, W.C. Oechel, J.H. Morison, T. Zhang, and R.G. Barry. 2000. Observational evidence of recent change in the northern high-latitude environment. Climatic Change 46(1/2):159-207.

Shaver, G.R., W.D. Billings, F.S. Chapin III, A.E. Giblin, K.J. Nadelhoffer, W.C. Oechel, and E.B. Rastetter. 1992. Global change and the carbon balance of arctic ecosystems. BioScience 42(6):433-441.

Sheehan, G.W. 1995. Whaling surplus, trade, war, and the interpretation of prehistoric northern and northwestern Alaskan economies, A.D. 1200-1826. Pp.185-206 in Hunting the Largest Animals: Native Whaling in the Western Arctic and Subarctic, A. McCartney, ed. Alberta: The Canadian Circumpolar Institute, University of Alberta.

Shelden, K., and D. Rugh. 1995. The bowhead whale, *Balaena mysticetus*, its historic and current status. Mar. Fish. Rev. 57(3-4):1-20.

Shepro, C.E., and D.C. Maas. 1999. North Slope Borough 1998/99 Economic Profile and Census Report, Vol. 8. Prepared for the North Slope Borough, Department of Planning and Community Services, Barrow, AK.

Shideler, R.T. 1986. Impacts of Human Developments and Land Use on Caribou: A Literature Review, Vol. 2. Impacts of Oil and Gas Development on the Central Arctic Herd. Technical Report No. 86-3. Juneau, AK: Division of Habitat, Alaska Dept. of Fish and Game.

Shideler, R., and J. Hechtel. 2000. Grizzly bear. Pp. 105-132 in The Natural History of An Arctic Oil Field, J.C. Truett, and S.R. Johnson, eds. San Diego: Academic Press.

Shotts, E.B., T.F. Albert, R.E. Wooley, and J. Brown. 1990. Microflora associated with the skin of the bowhead whale (*Balaena mysticetus*). J. Wildl. Dis. 26(3):351-359.

Shultz, G. 2001. Inspection of PGS Seismic Operation. Memorandum from G. Schultz, State of Alaska, Department of Natural Resources, to M. Rader, State of Alaska, Department of Natural Resources, Fairbanks, AK. August 6, 2001.

Simberloff, D. 1990. Hypotheses, errors, and statistical assumptions. Herpetologica 46(3):351-357.

Simmons, C.L., K.R. Everett, D.A. Walker, A.E. Linkins, and P.J. Webber. 1983. Sensitivity of Plant Communities and Soil Flora to Seawater Spills, Prudhoe Bay, Alaska. CRREL 83-24. Hanover, NH: U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory.

Simpson, T. 1855. Observations on the Western Esquimaux and the Country They Inhabit: From Notes Taken During Two Years at Point Barrow. (Bockstoce, J. 1988. Appendix 7. Pp. 501-550 in The Journal of Rochfort Maguire, 1852-1854: Two Years at Point Barrow aboard the H.M.S. Plover in the Search for Sir John Franklin, Vol. 2. London: Hakluyt Society).

Skogland, T. 1983. The effects of density-dependent resource limitation on size of wild reindeer. Oecologia 60(2):156-168.

Skogland, T. 1984. The effects of food and maternal conditions on fetal growth and size in wild reindeer. Rangifer 4(2):39-46.

Skok, M. 1991. Alaska's Red Dog Mine. Minerals Today (June):6 –13 [Online]. Available: http://imcg.wr.usgs.gov/usbmak/mt1.html [accessed Dec. 11, 2002].

Skoog, R.O. 1968. Ecology of Caribou (*Rangifer tarandus granti*) in Alaska. Ph.D. Thesis. University of California, Berkeley. 669pp.

Sloan, C.E. 1987. Water resources of the North Slope, Alaska. Pp. 233-252 in Alaskan North Slope Geology, Vol.1., I.L. Tailleur, and P. Weimer, eds. Special Pub. No. 50. Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, CA, and Alaska Geological Society Alaska, Anchorage, AK.

S.L. Ross (S.L. Ross Environmental Research, Ltd). 1998a. Evaluation of Cleanup Capabilities for Large Blowout Spills in the Alaskan Beaufort Sea During Periods of Broken Ice, Appendix G. Probability of Very Large Blowouts During Broken Ice Periods. Prepared for Alaska Clean Seas, Anchorage, AK, and Minerals Management Service, Anchorage, AK, by S.L. Ross Environmental Research, D.F. Dickins, and Vaudrey and Associates [Online]. Available: http://www.slross.com/publications/pubmain.htm [accessed June 20, 2002].

S.L. Ross (S.L. Ross Environmental Research, Ltd). 1998b. The Efficacy of In-Situ Burning for Alaskan Risk Oils. Final Report. Prepared for Alaska Department of Environmental

Conservation, and Alaska Clean Seas, Juneau, by S.L. Ross Environmental Research, Ltd, Ottawa, Ontario, Canada. June 1998.

S.L. Ross (S.L. Ross Environmental Research, Ltd). 1998c. Evaluation of Cleanup Capabilities for Large Blowout Spills in the Alaskan Beaufort Sea During Periods of Broken Ice, Appendix A. Background on Petroleum Activities in the Alaskan North Slope. Prepared for Alaska Clean Seas, Anchorage, AK, and Minerals Management Service, Anchorage, AK, by S.L. Ross Environmental Research, D.F. Dickins, and Vaudrey and Associates [Online]. Available: http://www.slross.com/publications/pubmain.htm [accessed June 20, 2002].

S.L. Ross (S.L. Ross Environmental Research, Ltd). 2000a. Dispersant Use for Spills in Ice-Infested Waters. Proceedings, International Oil and Ice Workshop 2000: Oil Spill Preparedness and Response for Cold Climates, April 5-7, 2000, Anchorage & Prudhoe Bay, Alaska. CD-ROM. Alaska Clean Seas.

S.L. Ross (S.L. Ross Environmental Research Ltd). 2000b. Test of an Annular Water Injection System for Pumping Emulsified Crude Oil. Prepared by S.L. Ross Environmental Research Ltd., Ottawa, Ontario, for Alaska Clean Seas, Anchorage, AK, U.S. Coast Guard, and U.S. Navy SUPSALV. December 2000.

S.L. Ross (S.L. Ross Environmental Research, Ltd). 2001. Effectiveness of Emulsion Breaker on North Slope Crude Oils. Draft Report. Prepared by S.L. Ross Environmental Research, Ltd., Ottawa, ON, for Alaska Clean Seas, Prudhoe Bay, AK. February 2001.

S.L. Ross/D.F.Dickins. (S.L. Ross Environmental Research, Ltd, and D.F Dickins Associates). 2001. Report on Phase 1 - Maximum Capacity Tests for the LORI Skimmer in Brash and Slush Ice. Second Draft Report. Prepared by S.L. Ross Environmental Research, Ltd, Ottawa, ON, and D.F Dickins Associates, Escondido, CA, for Alaska Clean Seas, Prudhoe Bay, AK. December 28, 2000.

Smith, M.D. 1996. Distribution, Abundance, and Quality of Forage Within the Summer Range of the Central Arctic Caribou Herd. M.S. Thesis. University of Alaska.

Smith, P.S., and J.B. Mertie. 1930. Geology and Mineral Resources of Nortwestern Alaska. U.S. Geological Survey Bulettin 815. Washington, DC: U.S. Govt. Print. Off.

Smith, R.A., J.R. Slack, T. Wyant, and K.J. Lanfear. 1982. The Oilspill Risk Analysis Model of the U.S. Geological Survey. Geological Survey Professional Paper 1227. Reston, VA: U.S. Dept. of the Interior, Geological Survey.

Smith, T.G. 1980. Polar bear predation of ringed and bearded seals in the land-fast sea ice habitat. Can. J. Zool. 58(12):2201-2209.

Smith, T.G., and L.A. Harwood. 2001. Observations of neonate ringed seals, *Phoca hispida*, after early break-up of the sea ice in Prince Albert Sound, Northwest Territories, Canada, spring 1998. Polar Biol. 24(3):215-219.

Smith, T.G., and I. Stirling. 1975. Breeding habitat of the ringed seal (*Phoca hispida*)-birth lair and associated structures. Can. J. Zool. 53(9):1297-1305.

Smith, T.G., M.O. Hammill, and G. Taugbøl. 1991. A review of the developmental, behavioral and physiological adaptations of the ringed seal, *Phoca hispida*, to life in the Arctic winter. Arctic 44(2):124-131.

Smith, W.T., and R.D. Cameron. 1983. Responses of caribou to petroleum development on Alaska's Arctic Slope. Acta Zool. Fenn. 175:43-45.

Smith, W.T., and R.D. Cameron. 1985a. Factors affecting pipeline crossing success of caribou. Pp. 40-46 in Caribou and Human Activity, Proceedings, First North Am. Caribou Workshop, Sept. 28-29, 1983, Whitehorse, Yukon, A.M. Martell, and D.E. Russell, eds. Ottawa: Canadian Wildlife Service.

Smith, W.T., and R.D. Cameron. 1985b. Reactions of large groups of caribou to a pipeline corridor on the Arctic Coastal Plain of Alaska. Arctic 38:53-57.

Smith, W.T., and R.D. Cameron. 1992. Caribou responses to development infrastructures and mitigation measures implemented in the Central Arctic Region. Pp. 79-86 in Terrestrial Research: 1002 Area-Arctic National Wildlife Refuge, Interim Report, 1988-1990, T.R. McCabe, B. Griffith, N.E. Walsh, and D.D. Young, eds. Anchorage, AK: Alaska Fish and Wildlife Research Center, Arctic National Wildlife Refuge.

Smith, W.T., R.D. Cameron, and D.J. Reed. 1994. Distribution and Movements of Caribou in Relation to Roads and Pipelines, Kuparuk Development Area, 1978-90. Alaska Dept. of Fish and Game, Juneau, AK. Wildl. Tech. Bull. No. 12. 54 pp.

Sonnenfeld, J. 1956. Changes in Subsistence Among Barrow Eskimo. Project No. ONR-140. Prepared for the Arctic Institute of North America.

Sonntag, R.M., W.T. Ellison, C.W. Clark, D.R. Corbit, and B.D. Krogman. 1986. A Description of a Tracking Algorithm and Its Implications to the Bowhead Whale Acoustic Location Data Collected During the Spring Migration Near Point Barrow, Alaska 1984-1985. Report of the International Whaling Commission 36:299-310.

Spencer, R.F. 1959. The North Alaskan Eskimo: A Study in Ecology and Society. Washington, DC: U.S. Government Printing Office.

Spraker, T.R., L.F. Lowry, and K.J. Frost. 1994. Gross necropsy and histopathological lesions found in harbor seals. Pp. 281-311 in Marine Mammals and the Exxon Valdez, T.R. Loughlin, ed. San Diego: Academic Press.

S.R. Braund and Associates. 1988. North Slope Subsistence Study-Barrow, 1987. Alaska OCS Sociocultural Studies Program Technical Report No. 133. Prepared by S.R. Braund and Associates, and Institute of Social and Economic Research, University of Alaska, for Minerals Management Service, Alaska OCS Region, Anchorage, AK.

S.R. Braund and Associates. 1989. North Slope Subsistence Study-Barrow, 1988. Alaska OCS Sociocultural Studies Program Technical Report No. 135. Prepared by S.R. Braund and Associates, and Institute of Social and Economic Research, University of Alaska, for Minerals Management Service, Alaska OCS Region, Anchorage, AK.

S.R. Braund and Associates. 1993. North Slope Subsistence Study-Barrow, 1987, 1988, and 1989. Alaska OCS Sociocultural Studies Program Technical Report No. 149. Prepared by S.R. Braund and Associates, and Institute of Social and Economic Research, University of Alaska, for Minerals Management Service, Alaska OCS Region, Anchorage, AK, and North Slope Borough, Barrow, AK.

Stanley, M.J., and B. Hazen. 1996. Insulated ice pad technology enables extended season drilling on Alaska's North Slope. SPE 35686. Pp. 359-367 in Proceedings: Western Regional Meeting, May 22-24,1966, Anchorage, AK. Richardson, TX: Society of Petroleum Engineers.

St. Aubin, D.J. 1990a. Physiological and toxic effects on pinnipeds. Pp. 103-127 in Sea Mammals and Oil: Confronting the Risks, J.R. Geraci, and D.J. St. Aubin, eds. San Diego: Academic Press.

St. Aubin, D.J. 1990b. Physiological and toxic effects on polar bears. Pp. 235-239 in Sea Mammals and Oil: Confronting the Risks, J.R. Geraci, and D.J. St. Aubin, eds. San Diego: Academic Press.

St. Aubin, D.J., R.H. Stinson, and J.R. Geraci. 1984. Aspects of the structure and composition of baleen, and some effects of exposure to petroleum hydrocarbons. Can. J. Zool. 62(2):193-198.

Steen, E. 1968. Some aspects of the nutrition of semi-domestic reindeer. Pp. 117-128 in Comparative Nutrition of Wild Animals, M.A. Crawford, ed. Symposia of the Zoological Society of London No. 21. London: Academic Press.

Stehn, R.A., C.P. Dau, B. Conant, and W.I. Butler. 1993. Decline of spectacled eiders nesting in western Alaska. Arctic 46(3):264-277.

Stephenson, R.O. 1979. Abundance, movements, and food habits of wolves in in and adjacent to NPR-A. Pp. 53-87 in Studies of Selected Wildlife and Fish and Their Use of Habitats on and Adjacent to National Petroleum Reserve in Alaska, 1977-1978, Vol. 1., Field Study 3., P.C. Lent, ed. Anchorage, AK: U.S. Dept. of Interior, National Petroleum Reserve in Alaska 105(c) Land Use Stady.

Stephenson, R.O. 1995. Game Management Unit 25A, 25B, 25D, 26B, and 26C brown bear management report. Pp. 271-288 in Brown Bear, Management Report of Survey-Inventory Activities, 1 July 1992-30 June 1994, M.V. Hicks, ed. Federal Aid in Wildlife Restoration Proj. W-24-1 and W-24-2. Juneau, AK: Alaska Dept. of Fish and Game, Division of Wildlife Conservation.

Stickney, A. 1991. Seasonal patterns of prey availability and the foraging behavior of arctic foxes (*Alopex lagopus*) in a waterfowl nesting area. Can. J. Zool. 69(11):2853-2859.

Stickney, A.A. 1996. Brant Use of the Oliktok LRRS and Movements in the Kuparuk Oil Field. Alaska Biological Research Inc., Fairbanks, AK.

Stickney, A.A., and R.J. Ritchie. 1996. Distribution and abundance of brant (*Branta bernicula*) on the central arctic coastal plain of Alaska. Arctic 49(1):44-52.

Stickney, A.A., R.J. Ritchie, B.A. Anderson, and D.A. Flint. 1994. Tundra Swan and Brant Surveys on the Arctic Coastal Plain, Colville River to Sagavanirktok River, 1993. Fairbanks, AK: Alaska Biological Research.

Stirling, I. 1988a. Attraction of polar bears to offshore drilling sites in the eastern Beaufort Sea. Polar Rec. 24:1-8.

Stirling, I. 1988b. Polar Bears. Ann Arbor: University of Michigan Press. 220 pp.

Stirling, I. 1990. Polar bears and oil: Ecological perspectives. Pp. 223-234 in Sea Mammals and Oil: Confronting the Risks, J.R. Geraci, and D.J. St. Aubin, eds. San Diego: Academic Press.

Stirling, I., and N.A. Øritsland. 1995. Relationships between estimates of ringed seal (*Phoca hispida*) and polar bear (*Ursus maritimus*) populations in the Canadian Arctic. Can. J. Fish. Aquat. Sci. 52(12):2594-2612.

Stirling, I., N.J. Lunn, and J. Iacozza. 1999. Long-term trends in the population ecology of polar bears in western Hudson Bay in relation to climate change. Arctic 52(3):294-306.

Stoker, S.W., and I.I. Krupnik. 1993. Subsistence whaling. Pp. 579-629 in The Bowhead Whale, J.J. Burns, J.J. Montague, and C.J. Cowles, eds. Special Publ. No. 2. Lawrence, KS: Society for Marine Mammalogy.

Stott, P.A., S.F.B. Tett, G.S. Jones, M.R. Allen, J.F.B. Mitchell, and G.J. Jenkins. 2000. External control of 20th century temperature by natural and anthropogenic forcings. Science 290(5499):2133-2137.

Streever, B. 2002. Science and emotion, on ice: The role of science on Alaska's North Slope. BioScience 52(2):179-184.

Sturm, M., J.P. McFadden, G.E. Liston, F.S. Chapin, C.H. Racine, and J. Holmgren. 2001. Snow-shrub interactions in arctic tundra: A hypothesis with climatic implications. J. Climate 14(3):336-344.

Tailleur, I.L. 1965. Low-volatile bituminous coal of Mississippian age on the Lisburne Peninsula, northwestern Alaska. Pp. B34-B38 in Geological Survey Research, 1965. U.S. Geological Survey Professional Paper 525-B. Washington, DC: U.S. G.P.O.

TAPS Owners (Trans Alaska Pipeline System Owners). 2001. Environmental Report for Trans Alaska Pipeline System Right-of-Way Renewal. Draft. Trans Alaska Pipeline System Owners [Online]. Available: http://tapseis.anl.gov/documents/report.cfm [accessed September 13, 2002].

Tarpley, R.J. 1985. Gross and Microscopic Anatomy of the Tongue and Gastrointestinal Tract of the Bowhead Whale (*Balaena mysticetus*). Ph.D. Thesis. Texas A&M University, College Station, TX. 141 pp.

Tarpley, R.J., and D.J. Hillmann. 1999. Observations on Ovary Morphology, Fetal Size and Functional Correlates in the Bowhead Whale *Balaena mysticetus*. Final report to Dept. of Wildlife Management, North Slope Borough, Barrow, AK, from Dept. of Veterinary Anatomy and Public Health, College of Veterinary Medicine, Texas A&M University, College Station, TX, and Dept. of Veterinary Anatomy and Cell Biology, School of Veterinary Medicine, Louisiana State University, Baton Rouge, LA.

Tarpley, R.J., R.F. Sis, M.J. Shively, and G. Stott. 1983. Structural Studies of the Alimentary, Reproductive and Skeletal Systems of the Bowhead Whale (*Balaena mysticetus*). Final Report. Prepared for the North Slope Borough, Barrow, AK, from the Dept. of Veterinary Anatomy, College of Veterinary Medicine, Texas A&M University, College Station, TX. 189 pp.

Tarpley, R.J., R.F. Sis, T.F. Albert, L.M. Dalton, and J.C. George. 1987. Observations on the anatomy of the stomach and duodenum of the bowhead whale, *Balaena mysticetus*. Am. J. Anatom. 180(3):295-322.

Tarpley, R.J., D.J. Hillmann, and J.C. George. 1999. Accumulation and Persistence of Corpora albicantia in the Bowhead Whale Ovary. Dept. of Veterinary Anatomy and Public Health, College of Veterinary Medicine, Texas A&M University, College Station, TX, Dept. of Veterinary Anatomy and Cell Biology, School of Veterinary Medicine, Louisiana State University, Baton Rouge, LA, and Dept. of Wildlife Management, North Slope Borough, Barrow, AK. Scientific paper SC/51/AS6 presented to the Scientific Committee of the International Whaling Commission, July 1999, Grenada, West Indies.

TERA (Troy Ecological Research Associates). 1993a. Bird Use of the Prudhoe Bay Oil Field. Prepared by Troy Ecological Research Associates, for BP Exploration (Alaska) Inc., Anchorage, AK.

TERA (Troy Ecological Research Associates). 1993b. Population Dynamics of Birds in the Pt. McIntyre Reference Area 1981-1992. Prepared by Troy Ecological Research Associates, for BP Exploration (Alaska) Inc., Anchorage, AK.

Thomas, H.F. 1946. A report on an expedition to the far north to locate rumored seeps and secure samples. The Oil Weekly (Feb. 4): 39-48.

Thomas, D.C. 1982. The relationship between fertility and fat reserves of Peary caribou *Rangifer tarandus*. Can. J. Zool. 60(4):597-602.

Thomas, D.C., and H.P.L. Kiliaan. 1998. Fire-Caribou Relationships. (II) Fecundity and Physical Condition in the Beverly Herd. Tech. Report No. 310. Canadian Wildlife Service, Prairie and Northern Region 1998. Edmonton: Canadian Wildlife Service. 96pp.

Thomson, B.R. 1977. The Behaviour of Wild Reindeer in Norway. Ph.D. Thesis. University of Edinburgh. 428 pp.

Tillman, M. 1980. Introduction: A scientific perspective of the bowhead whale problem. Mar. Fish. Rev. 42(9-10):1-5.

Tobai, S. 1997. Habitat loss and alteration in Japan-a history of large-scale destruction. Pp. 35-43 in Shorebird conservation in the Asia-Pacific Region, P. Straw, ed. Hawthorn East, Australia: Australasian Wader Studies Group of Birds Australia.

Toimil, L.J., and K.H. Dunton. 1983. Environmental Effects of Gravel Island Construction OCS-Y0191 (BF-37) Beechey Point, Block 480, Stefansson Sound, Alaska. Supplemental Study. Prepared for Exxon Company USA, by Harding Lawson Associates, Anchorage, Alaska. 56pp + appendices.

Toupin, B., J. Huot, and M. Manseau. 1996. Effect of insect harassment on the behaviour of the Riviere George caribou. Arctic 49(3):375-382.

Troy, D.M. 1996. Population dynamics of breeding shorebirds in arctic Alaska. Int. Wader Stud. 8:15-27.

Troy, D.M. 2000. Shorebirds. Pp. 277-303 in The Natural History of an Arctic Oil Field, J.C. Truett, and S.R. Johnson, eds. San Diego: Academic Press.

Troy, D.M., and T.A. Carpenter. 1990. The Fate of Birds Displaced by the Prudhoe Bay Oil Field: The Distribution of Nesting Birds Before and After P-Pad Construction. Prepared by Troy Ecological Research Associates, for BP Exploration (Alaska) Inc., Anchorage, AK.

Trudell, J., and R.G. White. 1981. The effect of forage structure and availability on food intake, biting rate, bite size and daily eating time of reindeer. J. Appl. Ecol. 18(1):63-81.

Trudel, K. 1986a. Marine birds. Pp.13-28 in Review of the Biological Fate and Effects of Oil in Cold Marine Environments, W.S. Duval, ed. Report EE-74. Prepared by ESL Evironmental Services, Ltd., S.L. Ross Environmental Research, Ltd, and Arctic Laboratories, Ltd., for Environmental Protection Service, Environment Canada, Ottawa, Ontario.

Trudel, K. 1986b. Fish. Pp. 77-99 in Review of the Biological Fate and Effects of Oil in Cold Marine Environments, W.S. Duval, ed. Report EE-74. Prepared by ESL Evironmental Services, Ltd., S.L. Ross Environmental Research, Ltd, and Arctic Laboratories, Ltd., for Environmental Protection Service, Environment Canada, Ottawa, Ontario.

Trudel, K. 1986c. Phytoplankton. Pp. 56-65 in Review of the Biological Fate and Effects of Oil in Cold Marine Environments, W.S. Duval, ed. Report EE-74. Prepared by ESL Evironmental Services, Ltd., S.L. Ross Environmental Research, Ltd, and Arctic Laboratories, Ltd., for Environmental Protection Service, Environment Canada, Ottawa, Ontario.

Trudel, K. 1986d. Zooplankton. Pp. 66-76 in Review of the Biological Fate and Effects of Oil in Cold Marine Environments, W.S. Duval, ed. Report EE-74. Prepared by ESL Evironmental Services, Ltd., S.L. Ross Environmental Research, Ltd, and Arctic Laboratories, Ltd., for Environmental Protection Service, Environment Canada, Ottawa, Ontario.

Truett, J.C., ed. 1993. Guidelines for Oil and Gas Operations in Polar Bear Habitats. MMS 93-0008. Anchorage, AK: U.S. Dept. of the Interior, Minerals Management Service, Alaska OCS Region. 104 pp.

Truett, J.C., and S.R. Johnson, eds. 2000. The Natural History of An Arctic Oil Field, San Diego: Academic Press.

Truett, J.C., R.G.B. Senner, K. Kertell, R. Rodrigues, and R.H. Pollard. 1994. Wild-life response to small-scale disturbances in arctic tundra. Wildl. Soc. Bull. 22:317-324.

Truett, J.C., M.E. Miller, and K. Kertell. 1997. Effects of arctic Alaska oil development on brant and snow geese. Arctic 50(2):138-146.

Trustees for Alaska. 2001. Drilling Waste Disposal. Oil in America's Arctic, Impacts of Oil Development on Alaska's North Slope. Trustees for Alaska, Anchorage, AK [Online]. Available: http://www.trustees.org/ [accessed August 14, 2002].

Tyler, N.J.C. 1987. Body composition and energy balance of pregnant and non-pregnant Svalbard reindeer during winter. Symp. Zool. Soc. Lond. 57:203-229.

Tynan, C.T., and D.P. DeMaster. 1997. Observations and predictions of Arctic climate change: Potential effects on marine mammals. Arctic 50(4):308-322.

Underwood, T.J., J.A. Gorden, M.J. Millard, L.A. Thorpe, and B.M. Osborne. 1995. Characteristics of Selected Fish Populations of Arctic National Wildlife Refuge Coastal Waters, Final Report, 1988-1991. Alaska Fisheries Technical Report No. 28. Fairbanks, AK: Fishery Resources Office, U.S. Fish and Wildlife Service. 590pp.

UNEP (C. Nellemann, L. Kullerud, I. Vistnes, B.C. Forbes, E. Husby, G.P. Kofinas, B.P. Kaltenborn, J. Rouaud, M.Magomedova, R. Bobiwash, C. Lambrechts, P.J. Schei, S. Tveitdal, O. Grøn, and T.S. Larsen). 2001. GLOBIO. Global Methodology for Mapping Human Impacts on the Biosphere. UNEP/DEWA/TR.01-3. 47pp. [Online]. Available: http://www.globio.info/region/polar/globioreportlowres.pdf [accessed Jan. 30, 2003].

USACE (U.S. Army Corps of Engineers). 1980. Prudhoe Bay Oil Field Waterflood Project: Prudhoe Bay, North Slope Borough, Alaska, Final Environmental Impact Statement. Anchorage, AK: U.S. Army Corps of Engineers, Alaska District.

USACE (U.S. Army Corps of Engineers). 1998. Draft Environmental Impact Statement, Beaufort Sea Oil and Gas Development/Northstar Project. U.S. Army Corps of Engineers Alaska District. Anchorage, AK: U.S. Army Engineer District, Alaska.

USACE (U.S. Army Corps of Engineers). 1999. Final Environmental Impact Assessment, Beaufort Sea Oil and Gas Development/Northstar Project. U.S. Army Corps of Engineers Alaska District. Anchorage, AK: U.S. Army Engineer District, Alaska.

U.S. Bureau of the Census. 1990. 1990 Census of Population. Washington, DC: U.S. Government Printing Office.

U.S. Bureau of the Census. 2000. U.S. Census 2000. U.S. Dept. of Commerce [Online]. Available: http://www.census.gov/ [accessed Nov. 27, 2002].

VanDyke, W., and D.H. Zobrist. 2001. Funding for Abondonment of Cook Inlet Alaska Oil and Gas Facilities: A landowner's perspectives. SPE 68853. Society of Petroleum Engineers Regional Meeting, Bakersfield, CA. March 2001.

van Tuyn, P. 2000. Environmental Community Perspective. Presented at Established Oil and Gas Practices and Technologies on Alaska's North Slope. Presented at Established Oil Technologies and Practices on Alaska's North Slope Workshop, April 2000, Anchorage, AK.

Van Valin, W.B. 1941. Eskimoland Speaks. Caldwell, ID: The Caxton Printers, Ltd.

Varo, M., and H. Varo. 1971. The milk production of reindeer cows and the share of milk in the growth of reindeer calves. Suomen Maataloustieteellinen Seura Maaataloustieteellinen Aik 43(1):1-10.

Vermeer, K. 1992. Population growth of the Glaucous-winged gull *Larus glaucescens* in the Strait of Georgia, British Columbia, Canada. Ardea 80(1):181-185.

Vilchek, G.E., and A.A.Tishkov. 1997. Usinsk oil spill: Environmental catastrophe or routine event? Pp. 411-420 in Disturbance and Recovery in Arctic Lands: An Ecological Perspective, R.M.M. Crawford, ed. Dordrecht: Kluwer.

Vinnikov, V.Y., A. Robok, R.J. Stouffer, J.E. Walsh, C.L. Parkinson, D.J. Cavalieri, J.F.B. Mitchell, D. Garrett, and V.F. Zakharov. 1999. Global warming and northern hemisphere sea ice extent. Science 286(5446):1934-1937.

Viscusi, W.K. 1992. Fatal Tradeoffs: Public and Private Responsibilities for Risk. New York: Oxford University Press.

Vistnes, I., and C. Nellemann. 2001. Avoidance of cabins, roads, and power lines by reindeer during calving. J. Wildl. Manage. 65(4):915-925.

Vourlitis, G.L., and W.C. Oechel. 1997. Landscape-scale CO_2, water vapour, and energy flux of moist-wet coastal tundra ecosystems over two growing seasons. J. Ecol. 85(5):575-590.

Vourlitis, G.L., and W.C. Oechel. 1999. Eddy covariance measurements of CO_2 and energy fluxes of an Alaskan tussock tundra ecosystem. Ecology 80(2):686-701.

Wahrhaftig, C., S. Bartsch-Winkler, and G.D. Stricker. 1994. Coal in Alaska. Pp. 937-978 in The Geology of Alaska, G. Plafker, and H.C. Berg, eds. The Geology of North America, Vol. G-1. Boulder, CO: Geological Society of America.

Waelbroeck, C., P. Monfray, W.C. Oechel, S. Hastings, and G. Vourlitis. 1997. The impact of permafrost thawing on the carbon dynamics of tundra. Geophys. Res. Lett. 24(3):229-232.

Walker, D.A. 1996. Disturbance and recovery of arctic Alaska vegetation. Pp. 35-71 in Landscape Function and Disturbance in Arctic Tundra, J.F. Reynolds, and J.D. Tenhunen, eds. Ecological Studies, Vol. 120. Berlin: Springer.

Walker, D.A. 1997. Arctic Alaskan vegetation disturbance and recovery. Pp. 457-479 in Disturbance and Recovery in Arctic Lands: An Ecological Perspective, R.M.M. Crawford, ed. Dordrecht: Kluwer.

Walker, D.A., and W. Acevedo. 1987. Vegetation and a Landsat-Derived Land Cover Map of the Beechey Point Quadrangle, Arctic Coastal Plain, Alaska. CRREL Report 87-5. Hanover, NH: U.S. Army Cold Regions Research and Engineering Laboratory.

Walker, D.A., and K.R. Everett. 1987. Road dust and its environmental impact on Alaskan taiga and tundra. Arc. Alp. Res. 19:479-489.

Walker, D.A., and K.R. Everett. 1991. Loess ecosystems of northern Alaska: Regional gradient and toposequence at Prudhoe Bay. Ecol. Monogr. 61(4):437-464.

Walker, D.A., and M.D. Walker. 1991. History and pattern of disturbance in Alaskan Arctic Terrestrial Ecosystems: A hierarchical approach to analysing landscape change. J. Appl. Ecol. 28(1):244-276.

Walker, D.A., and M.D. Walker. 1996. Terrain and vegetation of the Imnavait Creek Watershed. Pp. 73-108 in Landscape Function and Disturbance in Arctic Tundra, J.F. Reynolds, and J.D. Tenhunen, eds. Ecological Studies Vol. 120. Berlin: Springer.

Walker, D.A., P.J. Webber, K.R. Everett, and J. Brown. 1977. The Effects of Low-Pressure Wheeled Vehicles on Plant Communities and Soils at Prudhoe Bay, Alaska. CRREL Special Report 77-17. Hanover, NH: U.S. Army Cold Regions Research and Engineering Laboratory.

Walker, D.A., P.J. Webber, K.R. Everett, and J. Brown. 1978. Effects of crude and diesel oil spills on plant communities at Prudhow Bay, Alaska, and the derivation of oil spill sensitivity maps. Arctic 31(3):242-259.

Walker, D.A., K.R. Everett, P.J. Webber, and J. Brown. 1980. Geobotanical Atlas of the Prudhoe Bay Region, Alaska. CRREL Report 80-14. Hanover, NH: U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory.

Walker, D.A., M.D. Walker, K.R. Everett, and P.J. Webber. 1985. Pingos of the Prudhoe Bay region, Alaska. Arct. Alp. Res. 17(3):321-336.

Walker, D. A., E.F. Binnian, N.D. Lederer, E.A. Nordstrand, M.D. Walker, and P.J. Webber. 1986a. Cumulative Landscape Impacts in the Prudhoe Bay Oil Field 1949-1983. Final report. Prepared for U.S. Fish and Wildlife Service, Habitat Resources Section, Anchorage, AK.

Walker, D.A., P.J. Webber, M.D. Walker, N.D. Lederer, R.H. Meehan, and E.A. Nordstrand. 1986b. Use of geobotanical maps and automated mapping techniques to examine cumulative impacts in the Prudhoe Bay oil-field, Alaska. Environ. Conserv. 13(2):149-160.

Walker, D.A., D. Cate, J. Brown, et al. 1987a. Disturbance and Recovery of Arctic Alaskan Tundra Terrain: A Review of Recent Investigations. CRREL 87-11. Hanover, NH: U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory. 63 pp.

Walker, D.A., P.J. Webber, E.F. Binnian, K.R. Everett, N.D. Lederer, E.A. Nordstrand, and M.D. Walker. 1987b. Cumulative impacts of oil fields on northern Alaskan landscapes. Science 238:757-761.

Walker, D.A., N.A. Auerbach, J.G. Bockheim, F.S. Chapin III, W. Eugster, J.Y. King, J.P. McFadden, G.J. Michaelson, F.E. Nelson, W.C. Oechel, C.L. Ping, W.S. Reeburg, S. Regli, N.I. Shiklomanov, and G.L. Vourlitis. 1998. Energy and trace-gas fluxes across a soil pH boundary in the Arctic. Nature 394 (6692):469-472.

Walker, D.A., W.D. Billings, and J.G. de Molenaar. 2001a. Snow-vegetation interactions in tundra environments. Pp. 266-324 in Snow Ecology: An Interdisciplinary Examination of Snow-Covered Ecosystems, H.G. Jones, J.W. Pomeroy, D.A. Walker, and R.W. Hoham, eds. Cambridge: Cambridge University Press.

Walker, D.A., J.G. Bockheim, F.S. Chapin III, W. Eugster, F.E. Nelson, and C.L. Ping. 2001b. Calcium-rich tundra, wildlife, and the "Mammoth Steppe". Quat. Sci. Rev. 20(1):149-163.

Walker, D.A., W.A. Gould, H.A. Maier, and M.K. Raynolds. 2002. The Circumpolar Arctic Vegetation Map: AVHRR-derived base maps, environmental controls, and integrated mapping procedures. Int. J. Remote Sens. 23(21):4551-4570.

Walker, M.D. 1990. Vegetation and floristics of pingos, Central Arctic Coastal Plain, Alaska. Dissertationes Botanicae 149. Cramer, Stuttgart.

Walker, M.D., D.A. Walker, and K.R. Everett. 1989. Wetland Soils and Vegetation, Arctic Foothills, Alaska. Biological Report 89 (7). Washington, DC: U.S. Dept. of the Interior, Fish and Wildlife Service.

Walker, M.D., D.A. Walker, K.R. Everett, and S.K. Short. 1991. Steppe vegetation on south-facing slopes of pingos, Central Arctic Coastal Plain, Alaska, U.S.A. Arct. Alp. Res. 23(2):170-188.

Walker, H.J. 1983. Guidebook to Permafrost and Related Features of the Colville River Delta, Alaska. Guidebook 2. Fourth International Conference on Permafrost, July 18-22, 1983, University of Alaska, Fairbanks, AK [Online]. Available: http://www.dggs.dnr.state.ak.us/scan1/gb/text/GB2.PDF [accessed Jan.27, 2003].

Walsh, J.J., C.P. McRoy, L.K. Coachman et al. 1989. Carbon and nitrogen cycling within the Bering/Chuckchi Seas: Source regions for organic matter effecting AOU demands of the Arctic Ocean. Prog. Oceanogr. 22(4):277-359.

Walsh, N.E., S.G. Fancy, T.R. McCabe, and L.F. Pank. 1992. Habitat use by the Porcupine caribou herd during predicted insect harassment. J. Wildl. Manage. 56(3):465-473.

Washburn, A.L. 1980. Geocryology: A Survey of Periglacial Processes and Environments. New York: Wiley. 406pp.

Weimer, P. 1987. Northern Alaska exploration – the past dozen years. Pp. 31-37 in Alaska North Slope Geology, Vol.1, I.I. Tailleur, and P. Weimer, eds. Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, CA, and Alaska Geological Society Alaska, Anchorage, AK.

Weingartner, T.J. 1997. A review of the physical oceanography of the northeastern Chuckchi Sea. Pp. 40-59 in Fish Ecology in Arctic North America, J.B. Reynolds, ed. American Fisheries Society Symposium 19. Bethesda, MD: American Fisheries Society.

Weingarten, J.S., M.L. Bill, and D.E. Andrews. 2000. Confinement of wastes injected below thawed permafrost: A 12 year update from the North Slope of Alaska. SPE 62574. SPE/AAPG Western Regional Meeting Proceedings: June 19-23, 2000, Long Beach, CA. Richardson, TX: Society of Petroleum Engineers.

Weitzman, M.L. 2001. Gamma discounting. Am. Econom. Rev. 91(1):260-271.

Weladji, R.B., D.R. Klein, O. Holand, and A. Mysterud. 2002. Comparative response of *Rangifer tarandus* and other northern ungulates to climatic variability. Rangifer 22:33-50.

Weller, G.E. 2000. Marine mammal-sea ice relationships. Pp. 40-47 in Impacts of Changes in Sea Ice and Other Environmental Parameters in the Arctic, H.P. Huntington, ed. Bethesda, MD: U.S. Marine Mammal Commission.

Weller, M. W., K. C. Jensen, E. J. Taylor, M. W. Miller, K. S. Bollinger, D.V. Derksen, D. Esler, and C. Markton. 1994. Assessment of shoreline vegetation in relation to use by molting black brant *Branta bernicula nigricans* on the Alaska coastal plain. Biol. Conserv. 70(3):219-225.

Wells, P.G., J.N. Butler, and J.S. Hughes, eds. 1995. *Exxon Valdez* Oil Spill: Fate and Effects in Alaskan Waters. ASTM Tech. Pub. 1219. Philadelphia, PA: American Society For Testing and Materials.

West, R.L., and E. Snyder-Conn. 1987. Effects of Prudhoe Bay Reserve Pit Fluids on Water Quality and Macroinvertebrates of Arctic Tundra Ponds in Alaska. Biological Report 87-7. Washington, DC: U.S. Dept. of Interior, Fish and Wildlife Service.

Wheeler, P.A., M. Gosselin, E. Sherr, D. Thibault, D.L. Kirchmans, R. Benner, and T.E. Whitledge. 1996. Active cycling of organic carbon in the Central Arctic Ocean. Nature 380(6576):697-699.

White, R.G. 1983. Foraging patterns and their multiplier effects on productivity of northern ungulates: Reindeer, caribou and muskoxen, Alaska. Oikos 40(3):377-384.

White, R.G. 1992. Nutrition in relation to season, lactation and growth of north temperate deer. Pp. 407-417 in The Biology of Deer, R.D. Brown, ed. New York: Springer-Verlag.

White, R.G., and J.R. Luick. 1984. Plasticity and constraints in the lactational strategy of reindeer and caribou. Pp. 215-232 in Physiological Strategies in Lactation, R.G. Vernon, M. Peaker, and C.H. Knight, eds. Symposia of the Zoological Society of London No. 51. Orlando: Academic Press.

White, R.G., and J. Trudell. 1979. Patterns of herbivory and nutrient intake of reindeer grazing tundra vegetation. Pp. 180-195 in Proceedings of the Second International Reindeer/Caribou Symposium, Sept. 17-21, 1979, Roros, Norway, Part A, E. Reimers, E. Gaare, and S. Skjenneberg, eds. Trondheim: Direktoratet for vilt og ferskvannsfisk.

White, R.G., and J. Trudell. 1980. Habitat preference and forage consumption by reindeer and caribou near Atkasook, Alaska. Arct. Alpine Res. 12:511-529.

White, R.G., B.R. Thomson, T. Skogland, S.J. Person, D.E. Russell, D.F. Holleman, and J.R. Luick. 1975. Ecology of caribou at Prudhoe Bay, Alaska. Pp. 151-201 in Ecological Investigations of the Tundra Biome in the Prudhoe Bay Region, Alaska, J. Brown, ed. Biological Papers of the University of Alaska, Special Report. No. 2 . Fairbanks: University of Alaska.

White, R.G., F.L. Bunnell, E. Gaare, T. Skogland, and B. Hubert. 1981. Ungulates on arctic ranges. Pp. 397-483 in Tundra Ecosystems: A Comparative Analysis, L.C. Bliss, O.W. Heal, and J.J. Moore, eds. International Biological Programme Vol. 25. Cambridge: Cambridge University Press.

Whitten, K.R., and R.D. Cameron. 1979. Nutrient dynamics of caribou forage Alaska's Arctic Slope. Pp. 159-166 in Proceedings of the Second International Reindeer/ Caribou Symposium, Sept. 7-21, 1979, Roros, Norway, E. Reimers, E. Gaare, and S. Skjenneberg, eds. Trondheim: Direktoratet for vilt og ferskvannsfisk.

Whitten, K.R., and R.D. Cameron. 1983. Movements of collared caribou, *Rangifer tarandus*, in relation to petroleum development on the Arctic Slope of Alaska. Can. Field-Nat. 97:143-146.

Whitten, K.R., and R.D. Cameron. 1985. Distribution of caribou calving in relation to the Prudhoe Bay Oil Field. Pp. 35-39 in Caribou and Human Activity, Proceedings, the First North Am. Caribou Workshop, Sept. 28-29, 1983, Whitehorse, Yukon, A.M. Martell, and D.E. Russell, eds. Ottawa: Canadian Wildlife Service

Whitten, K.R., and R.D. Cameron. 1986. Groups vs individuals in the determination of caribou distribution. Pp. 325-329 in Proceedings of the 4th International Reindeer/ Caribou Symposium, August 22-25, 1985, Whitehorse, Yukon, Canada, A.Gunn, F.L. Miller, and S. Skjenneberg, eds. Rangifer, Spec.Issue No. 1. Harstad, Norway: Nordic Council for Reindeer Research.

Williams, J.R. 1970. Ground Water in the Permafrost Regions of Alaska. Geological Survey Professional Paper 696. Washington, DC: U.S. G.P.O. 83pp.

Williams, N. 1934. Practicability of drilling unit on Barges definitely established in Lake Barre, Louisiana Tests. Oil Gas J. (May 31):14-18.

Wildman, A.M., and R.J. Ritchie. 2000. Synthesis of Survey Information on Cliff-Nesting Raptors and Their Habitats on the North Slope, with an Emphasis on Peregrine Falcons and Recommendations for Survey Needs. Final report. Prepared for Northern Alaska Ecological Services, U.S. Fish and Wildlife Services, Fairbanks, AK, by ABR, Inc., Environmental Research and Services, Fairbanks, AK. November.

Wilson, W. 2001a. Marine Environment. Prepared by LGL Ecological Research Associates, Inc., Anchorage, AK, for Alaska Clean Seas, Anchorage, AK. April.

Wilson, W. 2001b. Marine Discharges. Prepared by LGL Ecological Research Associates, Inc., Anchorage, AK, for TAPS Owners, Anchorage, AK. May 2001.

Winters, J.F., P.K. Weber, A.L. DeCicco, and N. Shishido. 1988. An Annotated Bibliography of Selected References of Fishes of the North Slope of Alaska: With Emphasis on Research Conducted in National Petroleum Reserve-Alaska. Barrow, Alaska: Dept. of Wildlife Management, North Slope Borough.

Winters, J.F., and R.T. Shideler. 1990. An Annotated Bibliography of Selected References of Muskoxen Relevant to the National Petroleum Reserve – Alaska: for Department of Wildlife Management, North Slope Borough, Barrow. Habitat Division, Dept. of Fish and Game, Fairbakns, AK.

WMI (Wildlife Management Institute). 1991. Review of North Slope Alaska Caribou Research. Report to the Alaska Department of Fish and Game, Juneau, Wildlife Management Institute, Washington, DC.

Wolfe, S.A. 2000. Habitat Selection by Calving Caribou of the Central Arctic Herd, 1980-95. M.S. Thesis. University of Alaska Fairbanks, Fairbanks, AK. 83 pp.

Wondzell, B. 2000. Well Construction for Injection of Oilfield Wastes North Slope of Alaska. Presented at Established Oil Technologies and Practices on Alaska's North Slope Workshop, April 2000, Anchorage, AK.

Woodby, D.A., and D.B. Botkin. 1993. Stock sizes prior to commercial whaling. Pp. 387-407 in The Bowhead Whale, J.J. Burns, J.J. Montague, and C.J. Cowles, eds. Special Publ. No. 2. Lawrence, KS: Society for Marine Mammalogy.

Woodward, D.F., E. Snyder-Conn, R.G. Riley, and T.R. Garland. 1988. Drilling fluids and the arctic tundra of Alaska, U.S.A. assessing contamination of wetlands habitat and the toxicity to aquatic invertebrates and fish. Arch. Environ. Contam. Toxicol. 17(5):683-697.

Woodward-Clyde Consultants. 1980. Gravel Removal Studies in Arctic and Sub-arctic Floodplains in Alaska. FWS/OBS-80/08. Prepared for U.S. Fish and Wildlife Service, U.S. Dept. of Interior, Washington, DC, by Woodward-Clyde Consultants, Anchorage, AK.

Wooley/ARCO/BP (Wooley & Associates, Inc., ARCO Exploration and Production Technology, ARCO Alaska, Inc., and BP Exploration, Inc.). 1996. Assessment of Surface Casing Functional Integrity Requirements for North Slope Operations. Prepared by Wooley & Associates, Inc., Houston, TX, ARCO Exploration and Production Technology, Plano, TX, ARCO Alaska, Inc., Anchorage, AK, and BP Exploration, Inc., Anchorage, AK, for Alaska Oil and Gas Conservation Commission, Anchorage, AK. Nov. 20, 1996.

Wright, J.M., and S.G. Fancy. 1980. The Response of Birds and Caribou to the 1980 Drilling Operation at the Point Thomson #4 well. Final Report. Prepared for Exxon Co., by LGL Ecological Research Associates. Inc. Fairbanks, AK.

Young, D.D. and T.R. McCabe. 1998. Grizzly bears and calving caribou: What is the relation with river corridors? J. Wildl. Manage. 62(1):255-261.

Young, D.D, G. Garner, R. Ambrose, H. Reynolds, and T. McCabe. 1992. Differential impacts of predators (brown bears, wolves, golden eagles) on caribou calving in the 1002 area and potential displacement areas: An assessment of predation risks. Pp. 37-66 in Terrestrial Research: 1002 Area-Arctic National Wildlife Refuge, Interim Report, 1988-1990, T.R. McCabe, B. Griffith, N.E. Walsh, and D.D. Young, eds. Anchorage, AK: Alaska Fish and Wildlife Research Center, Arctic National Wildlife Refuge.

Young, D.D., T.R. McCabe, R. Ambrose, G.W. Garner, G.J. Weiler, H.V. Reynolds, M. S. Udevitz, D.J. Reed, and B. Griffith. 2002. Predators. Section 6 in Arctic Refuge Coastal Plain Terrestrial Wildlife Research Summaries, D.C. Douglas, and P.E. Reynolds, eds. Biological Science Report USGS/BRD/BSR-2002-0001. U.S. Geological Survey, Biological Resources Division[Online]. Available: http://alaska.usgs.gov/BSR-2002/usgs-brd-bsr-2002-001.html [accessed April 17, 2002].

Zeh, J., P. Turret, R. Gentleman, and A. Raftery. 1988. Population Size Estimation for the Bowhead Whale, *Balaena mysticetus*, Based on 1985 Visual and Acoustic Data. Report of the International Whaling Commission 38:349-364.

Zeh, J., A. Raftery, and Q. Yang. 1990. Assessment of Tracking Algorithm Performance and Its Effect on Population Estimates Using Bowhead Whales, *Balaena mysticetus*, Identified Visually and Acoustically in 1986 off Point Barrow, Alaska. Report of the International Whaling Commission 40:411-421.

Zhang, T., T.E. Osterkamp, and K. Stamnes. 1996. Some Characteristics of the climate in Northern Alaska, U.S.A. Arct. Alpine Res. 28(4):509-518.

Zhu, Q. 1996. Studies on the Eyes of the Bowhead Whale (*Balaena mysticetus*), Ringed Seal (*Phoca hispida*) and Caribou (*Rangifer tarandus*). Ph.D. Thesis. Institute of Oceanology, Chinese Academy of Sciences, Qingdao, Peoples Republic of China. 382 pp.

Zhu, Q. 1998. Some remarks on the structure of the eye of the bowhead whale, *Balaena mysticetus*. Report of the International Whaling Commission 48:497-499.

Zhu, Q., D.J. Hillmann, and W.G. Henk. 2000. Observations on the muscles of the eye of the bowhead whale, *Balaena mysticetus*. Anat. Rec. 259:189-204.

Zhu, Q., D. Hillmann, and W. Henk. 2001. Morphology of the eye and surrounding structures of the bowhead whale *Balaena mysticetus*. Mar. Mammal Sci. 17(4):729-750.