OIL SPILL PREVENTION and RESPONSE IN THE U.S. ARCTIC OCEAN

Unexamined Risks, Unacceptable Consequences

nuka Research & Planning Group, LLC.

(Photo credits for cover, clockwise from left: Oil rig, Stockbyte/Getty Images; spectacled eider, U.S. Fish and Wildlife Service; children, Burgess Blevins/Getty Images; bearded seal, Brendan Kelly. Background ice photo: Nuka Research and Planning LLC.)

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Scientific peer review conducted by three experts in oil spill response, oceanography and Arctic marine ecology.

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We also wish to thank the many people who helped make this report possible. Susan Harvey, Andrew Hartsig and Eric Jorgenson reviewed drafts of the report and provided extensive constructive criticism.

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EXECUTIVE SUMMARY

This report examine the risks, challenges and potential consequences of oil spills associated with oil and gas exploration and production in the outer continental shelf (OCS) of the United States Arctic Ocean. The April 2010 Deepwater Horizon well blowout in the Gulf of Mexico prompted a reconsideration of the potential for a major blowout from proposed oil exploration or production in the Arctic OCS. This report was developed to contribute to the policy discussion regarding the risks and consequences of such spills.

Several key concepts underlie the technical information and analysis presented in this report:

- The Arctic Ocean is a unique operating environment, and the characteristics of the Arctic OCS—its remote location, extreme climate and dynamic sea ice—exacerbate the risks and consequences of oil spills while complicating cleanup.
- Oil spill contingency plans often underestimate the probability and consequence of catastrophic blowouts, particularly for frontier offshore drilling in the U.S. Arctic Ocean.
- The impact of an oil well blowout in the U.S. Arctic Ocean could devastate an already stressed ecosystem, and there is very little baseline science upon which to anticipate the impact or estimate damage.
- Oil spill cleanup technologies and systems are unproved in the Arctic Ocean, and recent laboratory and field trials (including the Joint Industry Project) have evaluated only discrete technologies under controlled conditions.
- Certain environmental and weather conditions would preclude an oil spill response in the Arctic Ocean, yet an Arctic spill response gap is not incorporated into existing oil spill contingency plans or risk evaluations.

This report recommends several areas in which additional work is needed to reach a level of sufficient planning and preparedness to minimize the potentially adverse effects of an oil spill resulting from offshore oil and gas exploration or production in the U.S. Arctic Ocean. Federal agencies should:

1. Conduct baseline studies to better understand the marine ecosystem and increase scientific knowledge regarding the Arctic ecology and sensitivity to oil spills before introduction of new offshore oil spill risks.

(Photo credit: Arctic moon. *Mike Dunn/NOAA*)

2. Improve spatial data and mapping of Arctic species, habitat and sensitive ecosystems.
3. Develop oil spill trajectory models with the capability to model oil fate and behavior in the presence of a range of sea ice conditions.
4. Require operators to plan for the possibility of a worst-case well blowout and adopt all available engineering and management measures to prevent blowouts from occurring.
5. Conduct full-scale deployment exercises under a range of offshore Arctic conditions to determine the limits for safely and effectively mounting a large-scale offshore response in the U.S. Arctic Ocean.
6. Conduct an Arctic oil spill response gap analysis to delineate the upper operating limits of existing response technologies in the U.S. Arctic Ocean and then estimate the frequency and duration of periods when no oil spill response may be feasible.

INTRODUCTION 1

1.1 Purpose and Scope

The purpose of this report is to examine the risks, challenges and potential consequences of oil spills associated with oil and gas exploration and production in the outer continental shelf (OCS) of the U.S. Arctic Ocean.

The Arctic OCS refers to the federal waters[1] in the Beaufort and Chukchi Seas off the northern coast of Alaska (Figure 1-1). This remote, extreme northern portion of the OCS has a harsh environment with high winds, extended periods of heavy fog, seasonal darkness, subzero temperatures and weeklong storms. As a result, the risks, difficulties and unknowns of oil exploration in the Arctic OCS are far greater than in any other area of the OCS. Seasonal sea ice, lack of infrastructure, and distances from major population centers present challenges that may heighten the risks of a spill occurring while also limiting the potential effectiveness of spill cleanup technologies. The prospect of mounting a response to a catastrophic spill in the Arctic OCS is daunting, and the consequences of a major spill in this region could be dire. Scientific knowledge of Arctic ecology is based on incomplete information about marine mammals, fisheries and the marine ecosystem, and there are no computer models that can predict how an oil spill in the Arctic OCS would interact with that dynamic sea ice regime. Arctic regions are already under considerable strain from climate change, and Arctic species and ecosystems are highly sensitive to pollutants and much slower to recover from damage.

Most Americans will never see or visit the U.S. Arctic Ocean, and most are unaware of how the remote location and unique conditions of the Arctic OCS could limit the opportunity to contain or clean up an oil spill. Likewise, many Americans may be unaware of the potential harm of a catastrophic oil spill to the vibrant and iconic Arctic ecosystem. A primary goal of this report is to shed light on how and where existing oil exploration and production activities are conducted in the U.S. Arctic Ocean, to discuss proposed new activities, and to put into context the oil spill risks associated with these existing and new activities so that policymakers and stakeholders can make informed decisions regarding future oversight of oil exploration and production in the Arctic OCS.

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1 Subject to important reserved-land exceptions, Alaska has jurisdiction over submerged lands extending three miles from the coastline, and the federal government has jurisdiction over submerged lands from the three-mile mark to the seaward limit of the U.S. Exclusive Economic Zone, 200 miles from the coastline.

(Photo credit: Walrus. *U.S. Geological Survey/Sarah Sonsthagen*)

1.2 Background

The April 2010 Deepwater Horizon well blowout in the Gulf of Mexico provided a vivid illustration of a catastrophic oil spill resulting from exploratory drilling. The worst oil spill in U.S. history, and the largest well blowout worldwide, released at least 50,000 barrels per day for three months (Lubchenco *et al.* 2010). The blowout clearly exceeded the limits of existing technologies to contain and clean up marine oil spills, even in the temperate and accessible Gulf of Mexico.

Figure 1-1. U.S. Arctic OCS Region—The U.S. Arctic Ocean consists of the Chukchi Sea and the Beaufort Sea along the northern coastline of Alaska. State waters extend to three miles from the shoreline. Federal waters extend from the state water boundary to 200 miles from the shoreline, with the exception of some reserved land.

While the Deepwater Horizon well blowout continued in the Gulf of Mexico, Shell Oil began to prepare for exploratory drilling operations in federal waters of the Beaufort and Chukchi Seas. The Chukchi Sea drilling sites were located in an area of the U.S. Arctic Ocean where no oil exploration or production currently exists, and exploratory drilling was scheduled to begin in July 2010. The drilling was precluded, however, by Interior Secretary Ken Salazar's decision not to issue the required drilling permits in the Arctic OCS (Bureau of Ocean Energy Management, Regulation and Enforcement [BOEMRE] 2010).[2] Shortly thereafter, a federal court ruled that the Minerals Management Service (MMS)[3] did not comply with federal regulations when it approved Shell's plan to conduct exploratory drilling in that region of the Arctic OCS. This ruling, along with the lessons learned from the Deepwater Horizon spill and the increased scrutiny of the regulations and statutes governing oil exploration and production, has shed new light on the fact that federal oversight of oil exploration and production activities has not been duly diligent and that additional safeguards are needed to ensure that operators foresee and prepare for a worst-case oil spill. (U.S. Government Accountability Office 2010).

1.3 Key Concepts

This report was developed to contribute to the policy discussion regarding risks and consequences of oil spills from oil exploration and production in the Arctic OCS. The report builds on several previous studies, including two reports commissioned by WWF, that considered Arctic oil spill response technologies and planning concepts (DeCola *et al.* 2006, Nuka Research and Planning Group LLC 2007b, Nuka Research and Planning Group LLC 2007). Several key concepts underlie the technical information and analysis presented in this report.

1.3.1 The Arctic Ocean Is Different From Other Areas of the U.S. OCS

The U.S. Arctic Ocean is a unique part of the OCS whose characteristics exacerbate oil spill risks and consequences and present practical, logistical, technological and operational challenges. The Arctic environment, climate and weather affect all aspects of oil and gas exploration and production activities, but they are discussed in this report as they relate to potential oil spills.

> *"The Arctic imposes more than just an inhospitable climate. The remoteness dictates a different operating philosophy. Conventional road and rail access are unlikely to be available to the majority of ports bordering the Arctic seas. Beyond a fundamental lack of facilities, there is only a sparse resident population. Port facilities tend to be shallow (able to accommodate only barge and lightering type transfers), are only ice-clear and accessible a few months a year, and would not be expected to have heavy-lift facilities."*
>
> Keener and Allan 2009

Chapter 2 of this report provides an overview of the U.S. Arctic Ocean physical environment and describes existing and proposed oil exploration and production activities in the Arctic OCS. Chapter 2 also includes background information about drilling operations in the Arctic Ocean to provide a broader context for the discussion of how these challenges may increase the potential for an oil spill to occur. It details

2 On May 27, 2010, Interior Secretary Ken Salazar announced that his agency would not consider applications for permits to drill (APDs) for Shell's proposed exploration wells in the Beaufort and Chukchi Seas until 2011. In announcing the decision to delay, the Interior Department noted "the need for further information-gathering, evaluation of proposed drilling technology, and evaluation of oil spill response capabilities for Arctic waters."

3 On June 18, 2010, Interior Secretary Ken Salazar issued order No. 3302, reorganizing the MMS and renaming the agency BOEMRE. All references in this report to activities conducted before June 18, 2010, use the former agency title, MMS.

the challenges associated with containing and cleaning up an oil spill in this environment, and the potential harm that a major oil spill could cause to the region.

Figure 1-2. Arctic Coastline *(Photo: Mike Dunn/National Oceanic and Atmospheric Administration)*—The U.S. Arctic Ocean and its coastline have unique vulnerabilities to oil spills that should be factored into the decision-making process for new exploration or production.

1.3.2 Government and Industry Oil Spill Plans Underestimate Blowout Risks

Oil exploration and production create the potential for an accidental oil spill during all phases of activity. Chapter 3 of this report describes the spectrum of oil spill risks associated with offshore exploration and production in the Arctic OCS.

"Risk" is a product of probability and consequence. Understanding the risks associated with an activity require (1) the ability to predict the likelihood or probability of such an event occurring, and (2) the ability to anticipate the potential adverse consequences of such an event. Spill sizes and scenarios may range from a catastrophic well blowout to smaller spills from a pipeline, tank, or vessel. Very large oil spills and well blowouts are low probability events, but the consequences can be disastrous. Most of the planning that has been done to date in the U.S. Arctic Ocean expresses the risk of oil spills as being extremely low, based on probability estimates that have been derived from spill statistics in other regions of the United States.

There have been various estimates of oil spill "risks" in the U.S. Arctic Ocean, but none represents a comprehensive estimation of these risks. In order to reduce the potentially catastrophic impacts associated with uncontrolled oil spills from oil exploration in the Arctic OCS, it is first necessary to conduct a comprehensive risk assessment that provides a complete picture of the types of oil spills that may occur and to what those impacts might be. Specific measures must then be identified and put in place to reduce these risks either by reducing the probability of such events occurring, or putting measures in place to reduce the potential adverse consequence if a spill should occur. To do so requires a mature understanding of how and where spills might occur, and how the timing, size, and location of spills could impact the Arctic ecosystem in the short and long term.

> *"In the event of an unanticipated blowout resulting in an oil spill, it is unlikely to have an impact based on the industry-wide standards for using proven equipment and technology for such responses."*
>
> Oil Spill Response Plan for BP Deepwater Horizon Drilling
>
> *"A large oil spill, such as a crude release from a blowout, is extremely rare and not considered a reasonably foreseeable impact."*
>
> Shell Alaska Chukchi Sea Exploration Plan

1.3.3 An Oil Spill Could Devastate the Arctic Ecosystem

Although it is generally accepted that oil spills have the potential to cause significant harm to Arctic species and ecosystems, significant knowledge and science gaps still exist. Oil exploration and production activities have moved forward in the Arctic OCS against a backdrop of uncertainty regarding the potential impact of a major oil spill on Arctic wildlife, ecology and traditional human use. A 2007 assessment of worldwide oil and gas activities in Arctic regions emphasizes that the current state of knowledge regarding the impact of an Arctic oil spill is extremely limited. Knowledge is incomplete regarding environmental conditions, species composition and ecological interactions, as well as the potential impact on the people who rely on the Arctic Ocean for subsistence.

The impact of an oil spill in the Arctic Ocean would be influenced by the location and timing of the spill, the ice and weather conditions, and the inherent limitations of the spill response. Even a moderate-sized spill in an area where sensitive or threatened species are concentrated could have devastating effects. Similarly, oil that is spilled in the fall might become entrapped in newly forming sea ice and might not be accessible for cleanup and removal for many months. Many of the oil spill response plans developed by the industry for Arctic OCS drilling propose to concentrate oil spill response activities within open water areas that occur when sea ice is present. However, these open water areas—referred to as ice leads or polynyas—are a major source of nutrients in the Arctic and are considered to be

> *"Research is required on a wide range of the potential biological effects of these chemicals under conditions and with species and life stages appropriate to the Arctic, including, among others, studies of acute and chronic toxicity, genetic effects, and combined effects with, for example, exposure to sunlight. This includes studies of linkages between the diverse sub-lethal effects and the risks they pose to individuals and populations of Arctic animals."*
>
> Arctic Monitoring and Assessment Program 2008b

of vital importance to the entire marine food web, including marine mammals (Stirling 1997). Concentrating oil in these open water areas so that it could be burned or removed with skimmers would have unforeseen food web impacts and could increase the likelihood that marine mammals will contact the oil as they come up to breathe. Understanding and anticipating these potential interactions is critical to the spill planning process.

Policymakers and government oversight agencies cannot make informed decisions about oil spill risks and consequences without a better understanding of the basic ecological structures and populations of key indicator species in the U.S. Arctic Ocean. Chapter 4 of this report discusses the vulnerabilities of Arctic species and ecosystems to oil spill impacts, highlighting the gaps in our knowledge regarding the effects of a catastrophic oil spill on the Arctic ecosystem.

1.3.4 Oil Spill Response Systems Are Unproved in the Arctic Ocean

Even under ideal conditions, cleaning up an oil spill in the open water is a challenging task. The response estimates for the Deepwater Horizon spill show that approximately 25 percent of the spilled oil was mechanically removed from the environment through direct recovery from the wellhead, skimming or burning. Only 3 percent of the oil was mechanically recovered with skimmers and booms (Lubchenco *et al.* 2010). The 25 percent total is actually a very high success rate for a marine oil spill. If a major blowout were to occur in the Arctic OCS, the same mechanical cleanup techniques (boats with skimmers and booms) would be applied at a much less efficient recovery rate. Although some refinements have been made to adapt certain types of equipment for use in cold or ice-infested waters, there have been no breakthroughs in oil spill response technologies to significantly enhance the capacity to recover oil when sea ice is present. The National Academy of Sciences (NAS) determined that "no current cleanup methods remove more than a small fraction of oil spilled in marine waters, especially in the presence of broken ice" (National Research Council-NAS 2003).

> *"Today there is no proven response method for recovery of large-scale oil spills in ice-infested waters."*
>
> Evers *et al.* 2006

Chapter 5 describes the challenges associated with responding to oil spills in the remote and harsh Arctic climate and the limitations posed by the harsh operating environment and lack of infrastructure along the U.S. Arctic coast. Effective oil spill response in the Arctic OCS requires the demonstrated capacity to mount a large-scale effort using the existing limited infrastructure and to safely and effectively operate vessels and equipment under the harsh operating conditions typical of the Arctic OCS. The cold climate, seasonal sea ice, lack of infrastructure, and distance from major population centers adds a layer of complexity and challenge to all aspects of the response.

1.3.5 An Oil Spill Response Gap Exists

The Deepwater Horizon blowout shed new light on the potential for a worst-case subsea well blowout. A spill on the scale of the Deepwater Horizon in the U.S. Arctic Ocean would probably cripple the existing response technologies and infrastructure. Environmental and weather conditions in the Arctic Ocean make on-water oil spill response operations challenging, if not impossible. Yet the spill plans developed for U.S. Arctic Ocean exploratory drilling and approved by the former MMS were built around the assumption that if a blowout occurred in the U.S. Arctic Ocean, 95 percent of the oil would be contained or recovered before it hit the shoreline (Shell 2010). The much more moderate recovery estimates from the Deepwater Horizon spill—3 percent recovered through skimming, 17 percent recovered through subsea containment, 5 percent burned, in an area with much more favorable operating conditions (Lubchenco *et al.* 2010)—make the 95 percent assumption for the Arctic, or any water body, highly unrealistic.

> *"Adverse weather conditions sometimes preclude any response at all."*
>
> Oskins and Bradley 2005

Existing spill response systems will encounter limits during Arctic operations. There will be periods of times—days, weeks, or months—when environmental conditions will preclude any response at all. During such response gaps, an oil spill in the Arctic Ocean will be left untreated until weather or ice conditions improve enough that oil spill response systems can be operated. More work is needed to quantify the response gap for the Arctic Ocean.

Chapter 6 discusses the need to quantify the response limits to existing oil spill response systems in the U.S. Arctic Ocean and to base oil spill contingency planning on realistic assumptions regarding the manner in which sea ice, winds, waves and limited visibility may affect spill response operations.

1.4 Policy Recommendations

The key concepts presented in Chapters 2 through 6 of this report provide the basis for the policy recommendations in Chapter 7. The section presents recommendations for areas where additional research, planning, mitigation and oversight are needed to ensure that all future oil exploration and production activities in the Arctic OCS are conducted in a manner that minimizes spill risks, maximizes response capacity and ultimately prevents adverse impacts on the environment, ecology and indigenous people who rely on a healthy and pristine Arctic Ocean.

THE U.S. ARCTIC OCEAN 2

2.1 Characteristics of the Arctic OCS Environment

The Arctic region can be defined by latitude (the Arctic Circle at 60 degrees north) or by vegetation, temperature or other geographical or political boundaries (Hassol 2004, Arctic Monitoring and Assessment Program [AMAP] 1998). This report uses the term "Arctic" as broadly inclusive of areas where Arctic characteristics exist for part or all of the year. The term "U.S. Arctic Ocean," as used in this report, refers to the U.S. Beaufort and Chukchi Seas.[1] The term "Arctic OCS" refers specifically to federal waters (three to 200 miles from the shoreline, with the exception of some reserved land) in the Beaufort and Chukchi Seas (see Figure 1-1).

The physical environment of the Arctic Ocean off Alaska poses many challenges to oil exploration and production activities (Table 2-1). The U.S. Beaufort and Chukchi Seas can experience moving sea ice, subzero temperatures, extended periods of fog, and weeklong storms with extreme winds (International Arctic Research Center 2005). The brief Arctic summer has near-constant daylight, but the winter months are dominated by long hours of darkness and six weeks during which the sun never rises above the horizon. All of these factors affect oil exploration and production activities, but the physical characteristic of the Arctic OCS that most directly affects oil exploration and production is sea ice.

2.1.1 Climate

The U.S. Arctic Ocean and its adjacent coastline in northern Alaska experience an Arctic climate. The high-latitude marine region is situated off Russia's East Siberian coast and the northwestern and northern coasts of Alaska (Figure 1-1), where Pacific waters meet the Arctic Ocean via the Bering Strait. The region is characterized by major seasonal and annual changes in ocean climate and by the annual formation and deformation of sea ice (Section 2.1.2). Local winds strongly influence ice conditions near the coast. The warmest month in Barrow, Alaska, on the U.S. Arctic coast, typically is July, when the average temperature is around 39 degrees Fahrenheit. The days in Barrow with temperatures below the freezing point total 321 each year. The average temperature is near 30 degrees in September and near 13 degrees in October. Wind chill is a serious concern

1 The Northern Bering Sea meets the broadly inclusive definition of the Arctic region; however, the Northern Bering Sea is not discussed in this report because there are no existing or pending OCS drilling activities in that region.

(Photo credit: Arctic icicle. *Mike Dunn/NOAA*) for people and equipment operating in the U.S. Arctic, where the average annual wind speed is 12 mph. When the temperature is 30 degrees, a 12-mph wind creates a wind chill of 20 degrees; at 13 degrees, a 12-mph wind creates a wind chill of minus 1 degree (Western Regional Climate Center 2009a and 2009b).

Table 2-1. Arctic Conditions that May Affect Oil Exploration and Production Activities (AMAP 2008a, MMS 2007b and Grebmeier *et al*. 2010).

	Characteristics	*Relevance*
Physical Environment	*Cold*	Difficult work conditions, particularly in winter; slow weathering of oil compounds.
	Light/dark regime	Limited visibility and difficult work conditions in winter; extreme seasonality of biological production.
	Sea ice	Difficult site access and difficult operating conditions for vessels. Oil spill response systems may be ineffective. Spilled oil difficult to locate and track; may migrate with ice floes or become trapped/frozen.
	Wind and sea state	Hurricane-force storms in fall. Sea states producing up to 20 foot waves.
Biological Environment	*Seasonal aggregation of animals*	Major impacts possible even from localized spills or other disturbances.
	Migration	Impacts in the Arctic affect other parts of the world, and impacts elsewhere affect the Arctic.
	Short and efficient food webs	Disruption to key species may have cascading effects for other species.
Human Environment	*Remote, limited access*	Difficult to reach by air, water or land during emergency or oil spill, with limited capacity to transport equipment and personnel.
	Limited infrastructure	Lack of resources to support major spill response or other sudden influx of personnel and equipment.
	Small population	Significant demographic changes from industrial activities; influx of people from other places to support activities.
	Indigenous people	Impacts to subsistence food supply with potential for entire communities to face starvation conditions; impacts on local livelihood, culture, environment and indigenous rights and interests, including landownership.

The predominant summer winds in the U.S. Arctic Ocean are from the east and northeast, with speeds of 10 to 25 mph, but the major storm winds blow from the southwest, a direction that gives them maximum fetch (open-water distance over which to blow uninterrupted) for the southwest-facing coastline of the Chukchi Sea. The Beaufort Sea is more protected. The higher wind speeds progress northward beginning in the Bering Strait in June and continuing into the U.S. Arctic Ocean from July to October. In November and December, the maximum winds in the area start to decrease with a southward migration into the Chukchi Sea and eventually back through the Bering Strait into the Bering Sea, coincident with the sea ice retreat and advance in the area. The maximum daily average wind speed[2] for Barrow is highest in October (44 mph), November (40 mph) and December (35 mph). The yearly variance of wind speeds follows a similar

2 The maximum daily wind speed is the maximum speed measured over a 24-hour period.

northward and southward migration, and the highest variance happens in October. Wind data collected over the past 10 years from communities along the Chukchi and Beaufort seacoast show a substantial increase in the maximum wind speeds in September and October (Western Regional Climate Center 2009a and 2009b).

The Arctic climate has been affected by global climate change in several ways. One obvious impact has been changes to polar ice coverage, with a general decrease in multiyear sea ice (Section 2.1.2). Climate change has also resulted in an increased occurrence of "extreme events" in the Arctic region (IARC 2005). Atmospheric scientists use this term to describe a variety of weather occurrences, from single events to unusual climate variability lasting days or weeks. Examples of extreme events include heavy rains, dry spells, strong storms and winds, and extreme temperatures. During extreme events (Figure 2-1), atmospheric pressure at sea level, which is normally about 1,000 milibars, can drop to 30 to 70 milibars, creating enormous storm systems with hurricane-force winds (IARC 2005).

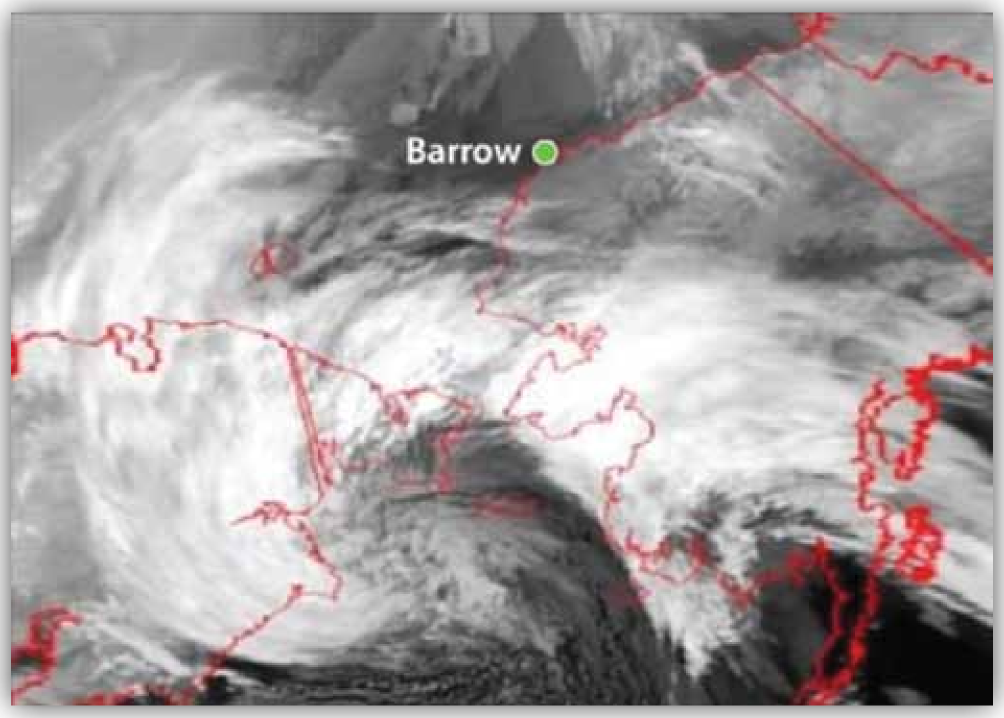


Figure 2-1. Major Arctic Ocean Storm System During October 2004 *(Source: IARC 2005)* (See Figure 1-1 for the location of Kivalina and Shishmaref in the Northwest Arctic)—This satellite image shows a major storm forming over the Bering Sea in October 2004. The extreme event pounded the northwest Arctic with 50- to 80-mph winds and caused coastal flooding and major wind damage. Extreme storm events have become more common in the U.S. Arctic Ocean, particularly the Chukchi Sea, as part of global climate change.

Storm surges often accompany major Arctic Ocean storm events, causing serious local flooding. The area most susceptible to storm surge flooding is north from Point Lay. Nearshore surface currents flow primarily northeast, parallel to the coast. Storms moving from the west or southwest can develop sufficient fetch for surges up to 10 feet during the ice-free period from July to October (Fontneau 1990). Many coastal communities along the U.S. Arctic Ocean are facing significant erosion because of these increasingly strong storm events (Figure 2-2).

Fog is also a major component of the Arctic Ocean climate (Figure 2-3). Low stratus clouds and advection fog are relatively common in the warmer months because of the passage of warmer air masses over the cold ice surfaces. Point Barrow averages 12 days of fog per month from May through September. During the winter, visibility can be limited by a combination of a short solar day, low sun angle, very light snowfall, occasional windblown snow, and low clinging fog over leads and other open-water areas. Air over open water in cold winter conditions becomes saturated almost immediately because of the low water-vapor capacity of cold air (Fontneau 1990).

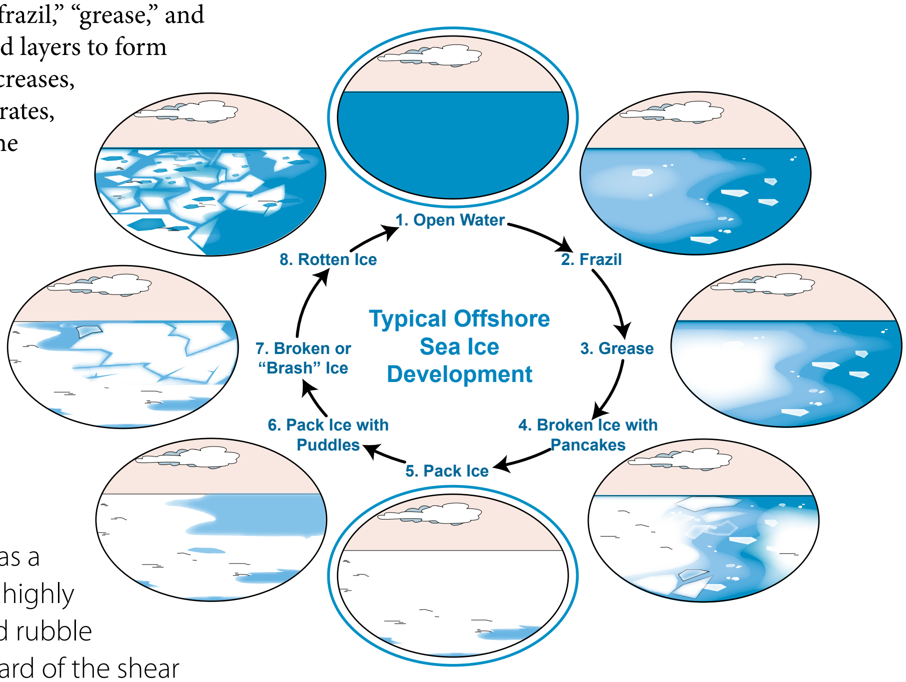
Figure 2-2. Erosion of the Arctic Ocean Shoreline Area *(Photo Credits: Left - USGS/Benjamin Jones, Below - Shishmaref Erosion and Relocation Commission)* (See Figure 1-1 for the location of Kivalina and Shishmaref)—Extreme storms are occurring more frequently in the Arctic Ocean, in part because of changes in sea ice coverage. Coastal erosion is causing a significant problem for several Alaska villages, including Kivalina (left) and Shishmaref (below).

Figure 2-3. Arctic Ocean Fog *(Photo Credits: Left - Dr. Pablo Clemente-Colon, Chief Scientist.* Sea ice melt pools provide some contrast for a vessel plying the Arctic Ocean in August 2009.

2.1.2 Sea Ice

Sea ice coverage varies by season and location. In the U.S. Arctic Ocean, sea ice is typically present eight months of the year, from October to June. During the summer, the Beaufort and Chukchi Seas experience a period of open water (predominantly ice-free, though scattered sea ice may be present) lasting approximately three months in the Beaufort and four months in the Chukchi. The brief ice-free summer ranges from late June to late October, depending upon location, distance from shore, and the conditions of each year. The Chukchi Sea tends to break up before the Beaufort and freeze up afterward. Sea ice formation and melting are cyclical, with ice taking on different forms (Figure 2-4). Freeze-up begins with "frazil" ice forming first as small pieces in open water. As frazil ice gradually thickens, it forms "grease" ice and "pancake" ice. Sheets of pack ice typically form by late October and persist until spring (late May into June). Breakup begins in June or July.

Figure 2-4. Typical Sea Ice Freeze-Up and Breakup Cycle—Sea ice formation and deformation are cyclic. The process through which sea ice begins to form on open water is dynamic and gradual, and ice conditions may vary and change considerably within a relatively small geographic area. Ice less than 10 cm thick constitutes new ice and includes "frazil," "grease," and "pancake" ice formations that build layers to form the pack ice. As solar radiation increases, melt ponds appear, melting accelerates, and cracks form, and eventually the ice disintegrates.



Throughout the eight- to nine-month ice season, solid or "fast" ice extends from the surface to the seabed at shallow depths and may continue out to water depths of 50 to 100 feet, where it transitions into what is known as a shear zone. The shear zone is a highly variable area where ridging and rubble occur (Eicken *et al.* 2006). Seaward of the shear zone is pack ice, which may encompass many types of sea ice. Pack ice contains young ice (newly formed and typically less than 30 cm thick), first-year ice and multiyear ice that has survived the previous summer melt season and can measure up to 10 meters thick (Arctic Council 2009). Figure 2-5 shows typical ice coverage for the U.S. Arctic Ocean based on satellite ice observations from four dates during 2007. Figures 2-6 and 2-7 show examples of Beaufort and Chukchi Sea ice coverage.

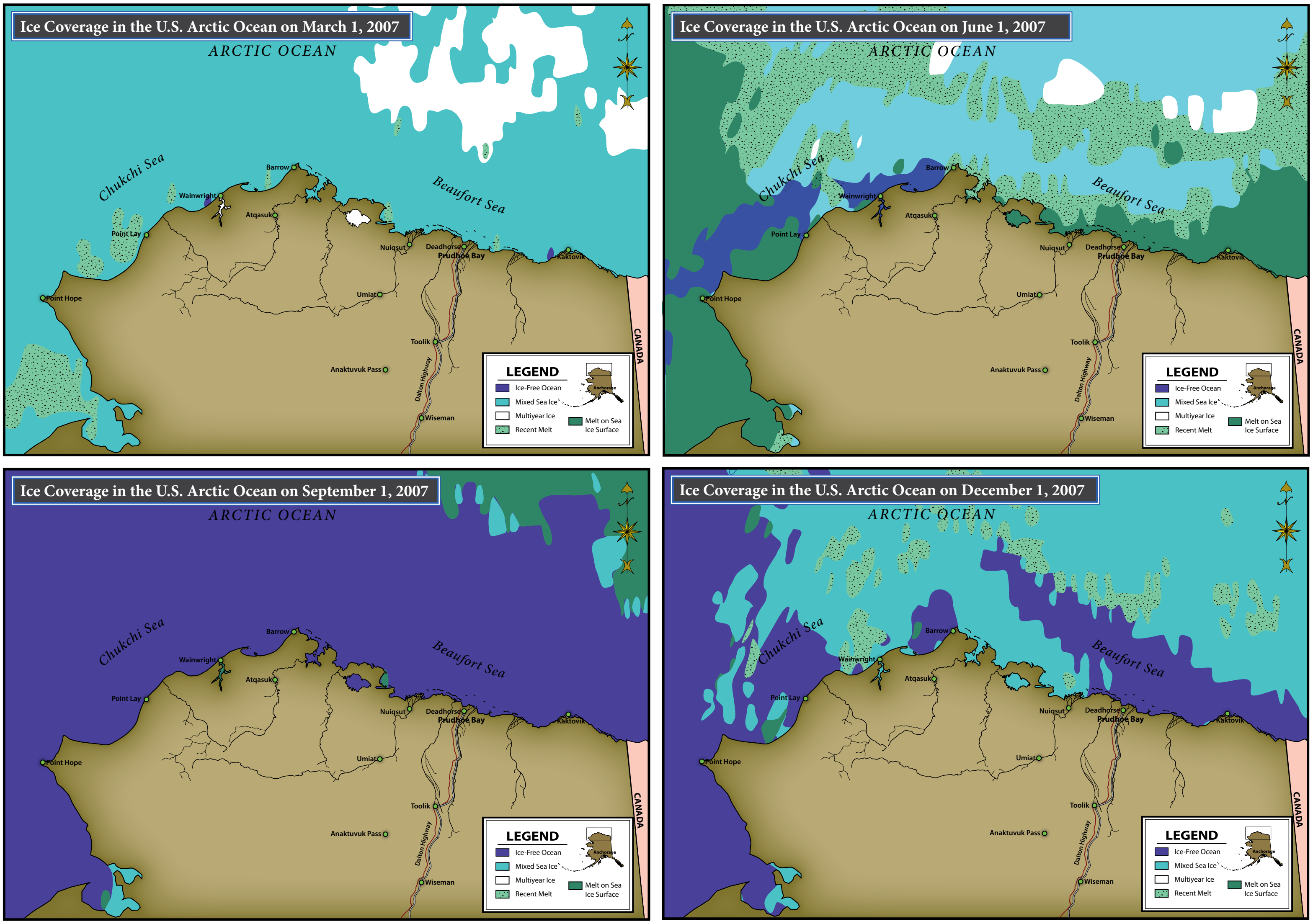


Figure 2-5. U.S. Arctic Ocean Sea Ice Maps—This series of maps shows the progression of U.S. Arctic Ocean ice represented by the ice coverage from four days in 2007, the year with the lowest ice concentration in recorded history. These maps are generally representative of Arctic ice conditions in March, June, September and December. September typically has the most open (ice-free) water, and March typically has the most solid (pack) ice. June and December are transitional ice periods: June shows the spring breakup, and December shows the fall freeze-up. Note that in December 2007, ice coverage was exceptionally low. In some years, there will be more land-fast ice in the Beaufort Sea by December. (Adapted from satellite images acquired from SIZONET 2010).

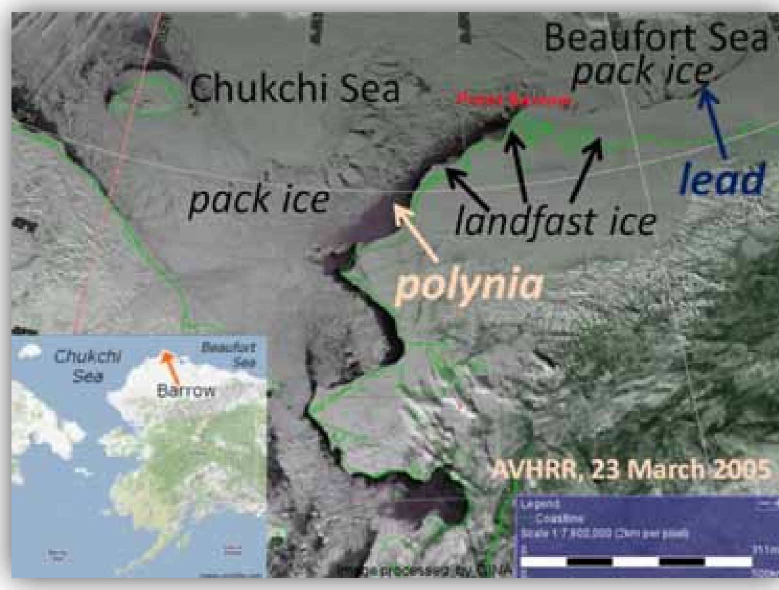
Sea ice is variable and complex, and the pack ice is constantly moving and shifting, with variability in a single season as well as from year to year. Shoreline ice is typically composed of large rubble and boulders, and the surface of the pack ice is highly textured (Figure 2-6 and 2-7). Several unique structures or formations may exist within and among the ice zones. For example, leads and polynyas[3] are openings that can occur in sea ice. Polynyas are caused by offshore wind conditions or warm water upwelling and are biologically rich areas with high rates of phytoplankton production. Polynyas are variable features and may open and close depending on conditions (AMAP 1998). Leads are openings in ice that are navigable by a vessel (WMO 2005). These, too, are variable, and they may occur naturally or be created using icebreaking vessels. Note that the satellite image in Figure 2-8 shows a large polynya present between the land-fast and pack ice. This large open-water area is important to biological productivity and is used by marine mammals for breathing (Chapter 4).

Figure 2-6. Shore-Fast Ice Between Barrow and Point Barrow *(Source: University of Alaska Fairbanks Geophyscial Institute 2010)*—A photograph shows shore-fast ice between Barrow and Point Barrow, Alaska, at the convergence of the Beaufort and Chukchi Seas. Shore-fast ice is present from October to June, with some variability. The photo was taken in June, just before the spring breakup. Note that more ice was present in June 2009 than in the June 2007 satellite image in Figure 2-5. Annual variations in sea ice coverage are particularly evident during the transitional ice seasons.

Figure 2-7. Surface of Pack Ice in the U.S. Arctic Ocean *(Photo Credit: Henry Huntington)*

3 Alternative spelling: polynia

Figure 2-8. Satellite Image Showing Ice Zones in the U.S. Arctic Ocean *(Source: University of Alaska Fairbanks Geophysical Institute 2010)*—Ice covers most of the U.S. Arctic Ocean from October to June. Openings known as polynyas (polynias) may occur. Some polynyas occur seasonally in the same location year after year, and others may be temporary. Multiyear recurring polynyas are ecologically significant to a number of Arctic species.



During the spring, melt ponds will form in the pack ice as it starts to break up and retreat, beginning with the inshore land-fast ice and moving seaward. Nearshore ice (shear zone) is the next to clear, typically by mid-July (Figure 2-9). The pack ice (typically in 70 feet or more of water) is the last to clear and is typically gone by early August (Eicken *et al*. 2006). The multiyear ice pack, which is located much farther offshore, has the potential to advance into ice-free areas during the open-water period, but this advancement has not occurred in the Beaufort or Chukchi in the past decade. During freeze-up and breakup, ice conditions can vary considerably by location and change rapidly over a short period (Eicken *et al*. 2006).

Sea ice conditions are in a state of flux because of global climate change. Minimum sea ice coverage (and thus maximum extent of open water) typically occurs in September. Observations from three decades of satellite imagery (1979-2008) suggest that the lowest sea ice coverage occurred during September 2007. Maximum sea ice coverage occurs in March, and observations from the past 30 years indicate that this coverage has decreased at a rate of approximately 2 percent per decade. The most significant declines to the thick multiyear sea ice occurred in the central Arctic Ocean, which was observed to decline at a rate of 7 percent per decade from 1978 to 1998 (Arctic Council 2009). Figure 2-10 illustrates historical changes in Arctic Sea ice coverage, with projections to 2040.

Global climate models developed as part of the Arctic Climate Impact Assessment (ACIA) indicate that summer ice-free areas in the Arctic Ocean are expected to expand considerably over the next century (Hassol 2004). However, there is no indication that winter sea ice coverage will completely disappear, meaning that the Arctic OCS will probably continue to have sea ice present in winter through at least the next century. Sea ice conditions may become more dynamic in coastal seas, with shorter periods of fast ice. These changes to Arctic sea ice are predicted to lead to an increase in Arctic shipping, which may increase the risk of oil spills or other accidents. (Arctic Council 2009).

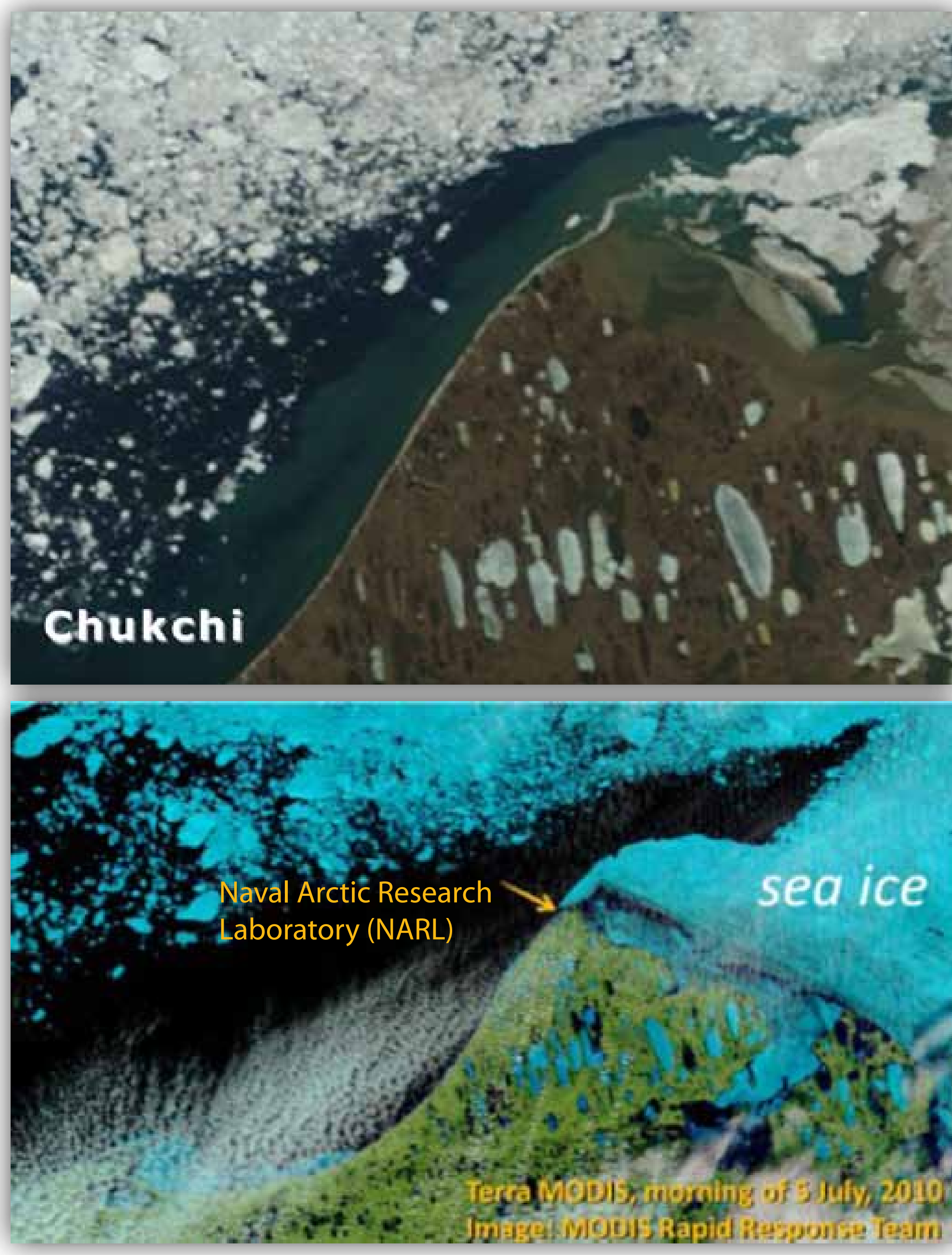


Figure 2-9. Images from Early July Ice Breakup, Point Barrow, Alaska, 2010 *(Source: University of Alaska Fairbanks Geophysical Institute 2010)*—Satellite image taken near Point Barrow, between the Chukchi Sea (to the west) and the Beaufort Sea (to the east). The image shows the final retreat of land-fast ice and the initiation of open water in the nearshore Chukchi Sea during July 2010.

Figure 2-10. Changes to September Ice Coverage in the Arctic, 1979-2009 *(Adapted from Arctic Council 2009 and National Snow and Ice Development Center 2010)*—Projected reductions in sea ice coverage suggest an increased area available to offshore development and shipping traffic through the Arctic Ocean.

2.2 Transportation Infrastructure

The Arctic OCS lies north and west of Alaska's North Slope, which is a remote and largely inaccessible region. The Dalton Highway (known as the "Haul Road") is the sole overland route to the U.S. Arctic Coast; it runs 415 miles from Livengood, near Fairbanks, to Deadhorse, which is in Prudhoe Bay adjacent to the Beaufort Sea. No roads link the Chukchi seacoast to the rest of Alaska or the continental United States (Figure 2-11).

Figure 2-11. Airstrips, Ports and Roads in the U.S. Arctic—The U.S. Arctic coastline in northern Alaska is sparsely populated with no major port or dock facilities and only a single road connecting Deadhorse, in the eastern part of the U.S. Arctic region, with the city of Fairbanks in central Alaska. There are no roads connecting the widely scattered communities.

The North Slope region includes eight main communities (Anaktuvuk Pass, Atqasuk, Barrow, Kaktovik, Nuiqsut, Point Hope, Point Lay and Wainwright), and they are not connected to each other by road or to the rest of the state by highway. (Figure 2-12 shows an aerial view of Wainwright.)

The regionwide population is approximately 7,400 people (2000 census data). Most of these communities have airstrips or small airports and small docks or boat ramps that provide the primary transportation link into the communities. People and materials coming into these small airports are then moved around via snow machine in the winter, and with ATVs or other vehicles along unpaved roads or by vessels over water in the summer. Travel over land is particularly challenging in the Arctic summertime, because the thawed tundra is easily damaged by tire tracks or even footprints. In the winter, overland travel is easier because the frozen tundra may be traversed by snow machine or ATV, and ice roads may be constructed to support larger vehicles (Figure 2-13). However, ice roads require time and a large supply of water to construct. An ice road six inches thick and 30 to 35 feet wide would require approximately 1 million to 1.5 million gallons of water per mile and could cost $200,000 to $250,000 per mile to construct and maintain (Department of Energy/National Energy Technology Laboratory 2007).

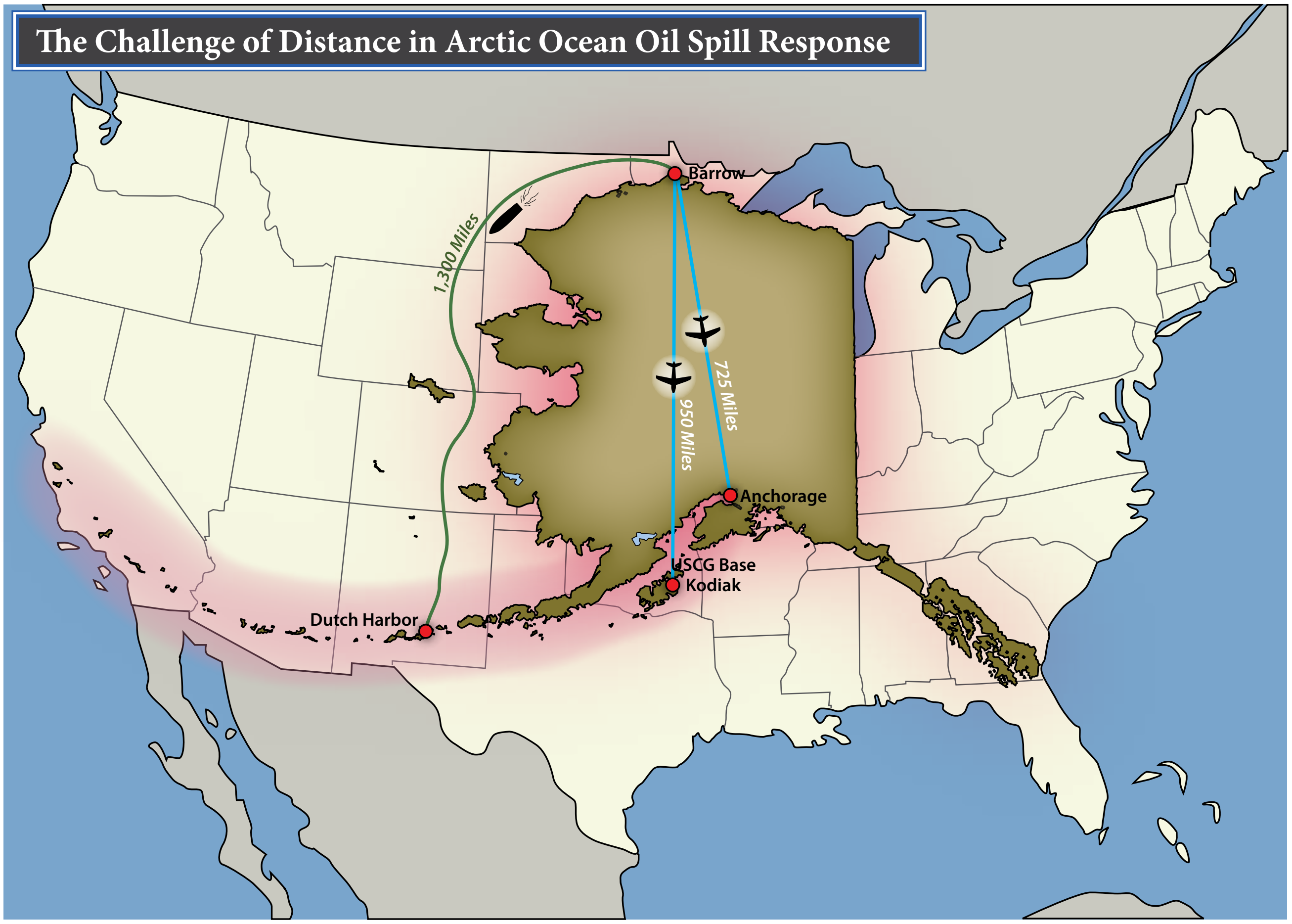
Figure 2-12. Wainwright, Alaska *(Photo Credit: Henry Huntington)*—Wainwright is the second-largest town in Alaska's North Slope Borough. The total population as of the 2000 census was 546 people. Temperatures in Wainwright range from 56 degrees below zero to 80 degrees F. A 4,500-foot-long gravel runway allows plane access, but Wainwright is not connected to a road system and has no port facilities. The coastline is frozen from late October through early July.

Figure 2-13. Overland Transportation Options in the U.S. Arctic During Winter *(Photo Credit: U.S. Army)*—Overland travel is extremely challenging during the brief Arctic summer because of the lack of a road system. Ice roads (right) may also be constructed during the winter, but one mile of ice road may require as much as 1.5 million gallons of water and can cost up to $250,000 to construct.

Docks are limited along the U.S. Arctic coast, and shallow water depths along the shoreline make vessel access challenging (Figure 2-14). The nearest major port (Unalaska's Dutch Harbor, in the Aleutian Islands) is 1,300 nautical miles from Point Barrow. There are limited airstrips, a few with the ability to accommodate larger cargo planes, but these are not connected to a road system. The nearest U.S. Coast Guard air station is 950 air miles away in Kodiak, Alaska, and no Coast Guard vessels reside in the Beaufort or Chukchi Seas (Figure 2-15).

Figure 2-14. Lack of Major Docks or Ports in the U.S. Arctic Ocean *(Photo Credit: Petty Officer 1st Class David Mosley/USGC)*—With no major docks available, shallow draft barges and landing craft pull right onto the beach during ice-free months. Large vessels cannot navigate close to shore and must remain in deeper water, transferring their supplies or passengers to smaller boats capable of beach landings. To launch small boats, the Coast Guard crews must uncover a boat ramp at Barrow.

Figure 2-15. Distance from Barrow, Alaska (in U.S. Arctic Ocean), to Nearest Major Port (Dutch Harbor) and Nearest Coast Guard Air Station (Kodiak) —Barrow, Alaska, is the northernmost community in the United States, located adjacent to the Arctic Ocean at the confluence of the Beaufort and Chukchi Seas. There are no major docks or port facilities in Barrow or anywhere on the U.S. Arctic coast, nor are there U.S. Coast Guard cutters or aircraft. The nearest major port is 1,300 miles away in Dutch Harbor. The nearest U.S. Coast Guard air station is 950 air miles away in Kodiak, Alaska. The map below illustrates the distances relative to the U.S. mainland.



3 OIL EXPLORATION, PRODUCTION OPERATIONS AND SPILL RISKS IN THE ARCTIC OCEAN

The process of extracting oil and gas from reservoirs in the Arctic OCS region is conducted in two broad phases: exploration, during which oil companies conduct studies to determine where oil and gas reservoirs are located and how the oil may be extracted from them, and production, during which more permanent operations are established to extract the oil. Exploration involves drilling wells into oil reservoirs under the ocean, and production of oil from wells in the Arctic Ocean involves pumping oil from the subsea wells using a range of technologies. (Section 3.2 describes the basic mechanics of drilling.)

Before an oil company can commence with exploratory drilling in the United States, it must purchase a lease. Leasing for oil exploration and production from subsea reservoirs in federal waters is managed by the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE, formerly the Minerals Management Service) under a five-year planning program. Once a lease has been secured and the Interior Department has approved the exploration plan, exploration can begin, typically starting with seismic studies and other surveys to assess the oil and gas production potential, then moving to exploratory drilling in areas considered to have the highest potential. If viable reservoirs are discovered through exploratory drilling, the operator will move on to oil production. This process takes several years, and a range of permits and plans are required.

This section describes the basic mechanics of oil exploration and production operations and provides a brief history of oil exploration in state and federal waters of the U.S. Beaufort and Chukchi Seas. The challenges of oil exploration and production in the Arctic Ocean are discussed, and the risks of spills from various phases of exploration and production are considered.

Because there is currently no offshore oil production in waters deeper than 100 feet in the U.S. Arctic Ocean, the oil production technologies discussed here are based on current or proposed technologies in other Arctic countries.[1]

1 The description of oil production in waters deeper than 100 feet is presented for discussion purposes only; the authors do not suggest that these operations are feasible in the U.S. Arctic Ocean.

(Photo credit: Oil rig, *Stockbyte/Getty Images*)

3.1 Historical Perspective on Oil and Gas in the Arctic Ocean

3.1.1 Worldwide

Offshore exploratory drilling and/or oil production has taken place in several Arctic regions, including the Canadian Beaufort Sea, West Greenland, the Norwegian Sea, the Barents Sea, the West Siberian Basin and the Far East Siberian Basins. The Arctic currently produces about one-tenth of the world's oil and a quarter of its gas, and Russia is by far the highest-producing Arctic nation, contributing 80 percent of total Arctic oil production and 99 percent of Arctic gas (AMAP 2008a). Most of this Arctic activity has been concentrated onshore, particularly in the United States. (Figure 3-1).

Figure 3-1. Arctic Oil and Gas Provinces and Basins, Showing Existing and Pending Production in the Arctic Ocean Worldwide *(Adapted from AMAP 2008a and Anderson 2010)*—Although there are a number of major oil and gas provinces and basins in the Arctic region, oil production in the worldwide Arctic has been concentrated primarily on land. Increased exploration and production in the Arctic Ocean is expected as a result of new drilling technologies and reductions in sea ice coverage.

A combination of factors, including decreasing production from existing reservoirs, new oil exploration technologies, and reductions in Arctic ice coverage have led to recent increases in oil activities in the Arctic Ocean. Exploration and production from marine facilities farther offshore in the Arctic Ocean create challenges for operators (Arctic Council 2009 and AMAP 2008a).

3.1.2 United States Arctic Ocean

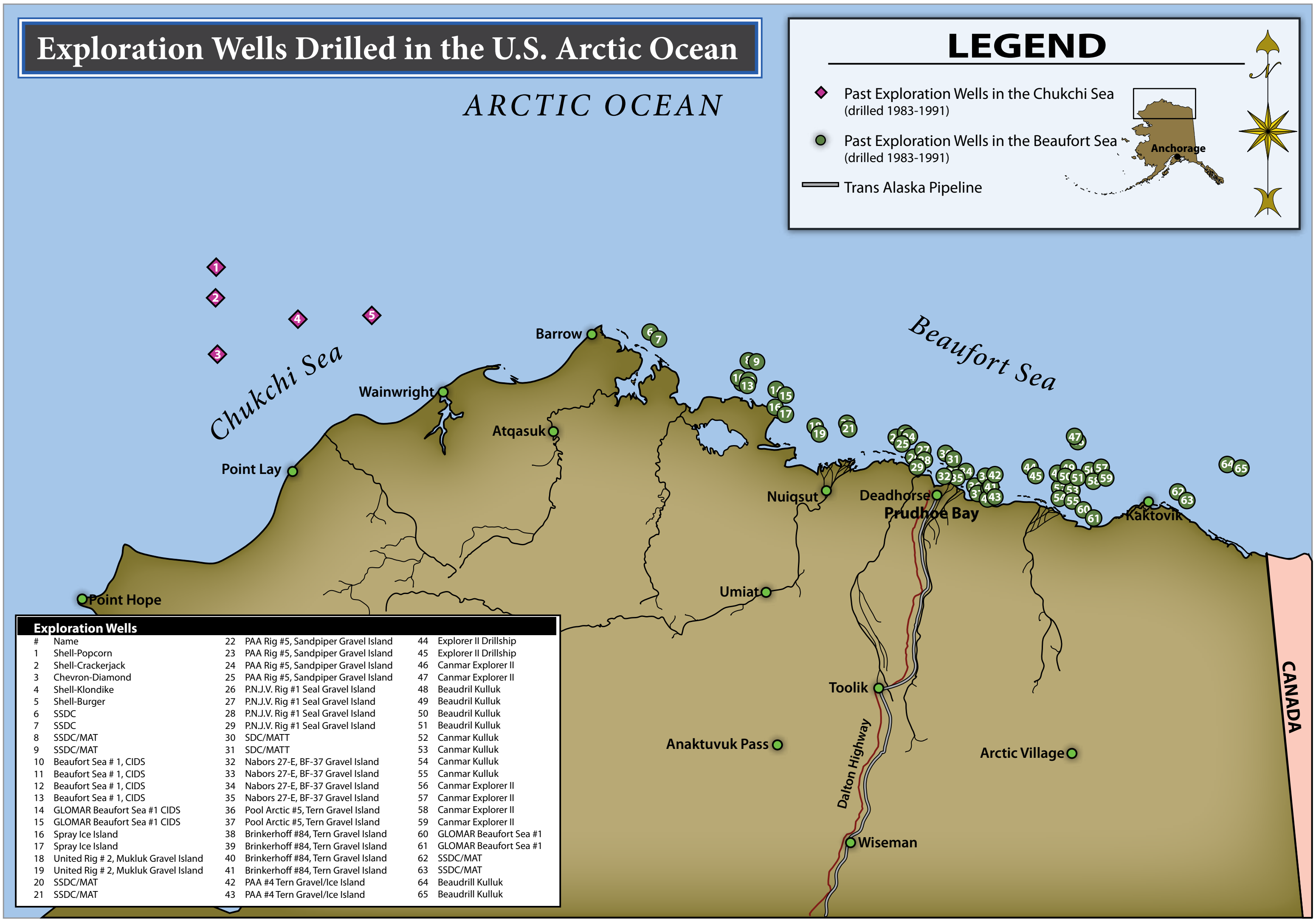
In the U.S. Arctic, oil exploration began in the 1960s and production began in 1977, 10 years after the discovery of the Prudhoe Bay oil field. That year, the Trans-Alaska Pipeline System (TAPS) was completed, connecting Prudhoe Bay production units with a major oil terminal in Valdez, Alaska. The majority of the existing oil production infrastructure and oil fields in Northern Alaska are located on land and in state waters of the Prudhoe Bay in the Beaufort Sea.

Although oil production in the U.S. Arctic Ocean remains clustered in state and nearshore federal waters in Prudhoe Bay, some exploration drilling has taken place in federal waters father offshore in the Beaufort and Chukchi Seas. Exploratory drilling in the Arctic OCS was most prevalent for about a 10-year period beginning in the mid-1980s. Figure 3-2 shows sites where past exploratory drilling has been conducted in the U.S. Arctic Ocean. A few of those exploratory drilling projects resulted in production from state and federal waters in the U.S. Beaufort Sea from artificial islands near Prudhoe Bay (Figure 3-3). There are no production operations in the Chukchi Sea.

Exploration activities in the Arctic OCS declined during the 1990s and into the 2000s. Although lease sales continued during this period, little exploratory drilling resulted. There is no concise reason for this trend, but it is reasonable to assume that declining oil prices contributed to an economic disincentive to continue exploration in these frontier seas.

No new exploratory drilling has taken place in the Chukchi Sea since the early 1990s. In 2008, the MMS held Lease Sale 193, and as a result of that sale, oil companies leased 2.75 million acres in the Chukchi Sea. Several active leases exist in the Beaufort Sea from past lease sales (Figure 3-4). Exploratory drilling was planned for the Chukchi and Beaufort Seas in 2010 but was put on hold because of Interior Secretary Ken Salazar's decision not to approve final drilling permits in the wake of the Deepwater Horizon disaster.[2]

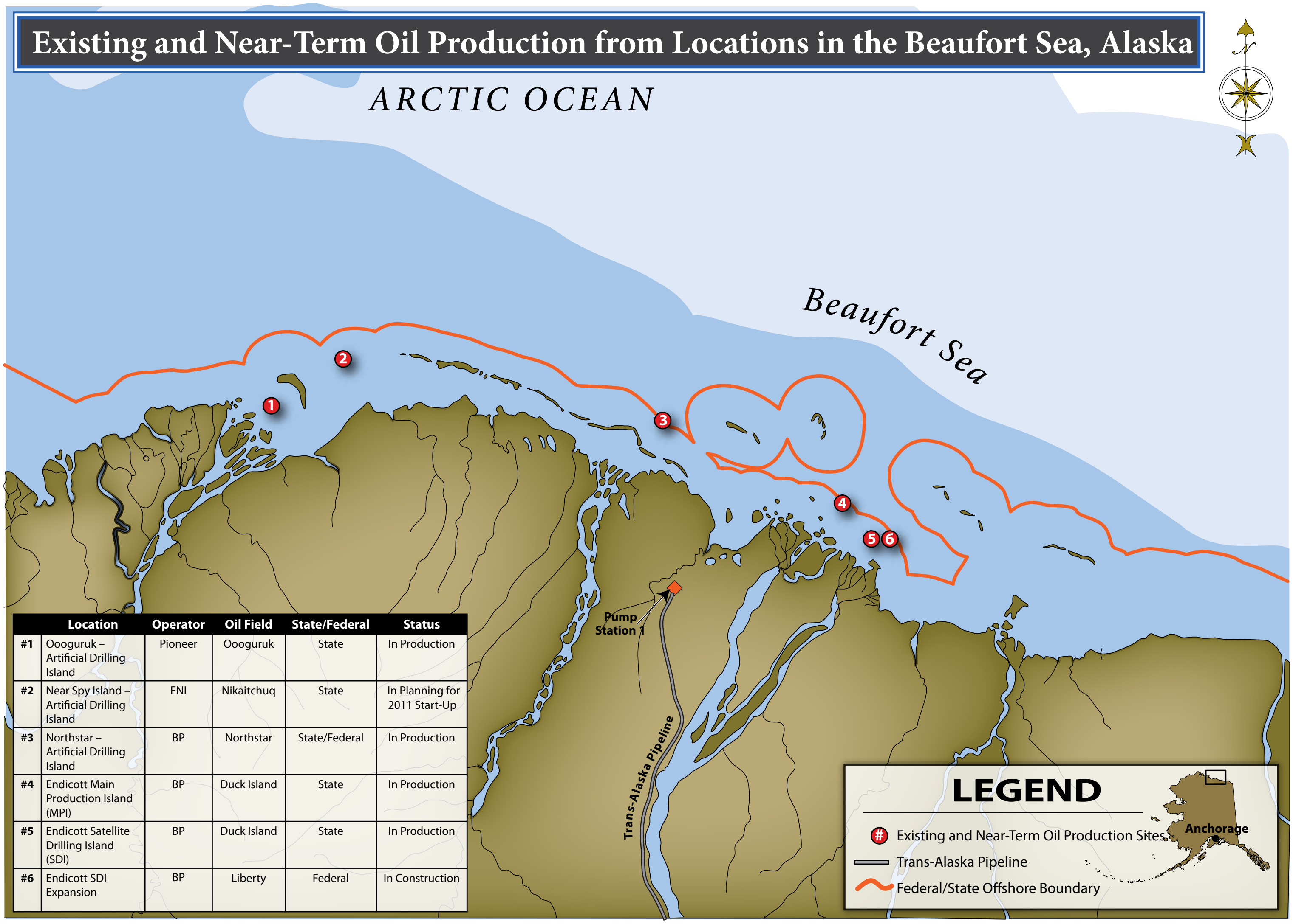
2 Several conditions probably must be met before Shell can proceed with exploratory drilling in the Chukchi Sea: (1) DOI must finalize its revised five-year leasing program for 2007-2012; (2) DOI must complete additional analysis of Lease Sale 193 to comply with an order of a federal district court; (3) DOI must approve Shell's application for a permit to drill; and (4) the Environmental Appeals Board (an independent body within the EPA) must issue a decision on Shell's air permit under the Clean Air Act.



Exploration Wells

#	Name	#	Name	#	Name
1	Shell-Popcorn	22	PAA Rig #5, Sandpiper Gravel Island	44	Explorer II Drillship
2	Shell-Crackerjack	23	PAA Rig #5, Sandpiper Gravel Island	45	Explorer II Drillship
3	Chevron-Diamond	24	PAA Rig #5, Sandpiper Gravel Island	46	Canmar Explorer II
4	Shell-Klondike	25	PAA Rig #5, Sandpiper Gravel Island	47	Canmar Explorer II
5	Shell-Burger	26	P.N.J.V. Rig #1 Seal Gravel Island	48	Beaudril Kulluk
6	SSDC	27	P.N.J.V. Rig #1 Seal Gravel Island	49	Beaudril Kulluk
7	SSDC	28	P.N.J.V. Rig #1 Seal Gravel Island	50	Beaudril Kulluk
8	SSDC/MAT	29	P.N.J.V. Rig #1 Seal Gravel Island	51	Beaudril Kulluk
9	SSDC/MAT	30	SDC/MATT	52	Canmar Kulluk
10	Beaufort Sea # 1, CIDS	31	SDC/MATT	53	Canmar Kulluk
11	Beaufort Sea # 1, CIDS	32	Nabors 27-E, BF-37 Gravel Island	54	Canmar Kulluk
12	Beaufort Sea # 1, CIDS	33	Nabors 27-E, BF-37 Gravel Island	55	Canmar Kulluk
13	Beaufort Sea # 1, CIDS	34	Nabors 27-E, BF-37 Gravel Island	56	Canmar Explorer II
14	GLOMAR Beaufort Sea #1 CIDS	35	Nabors 27-E, BF-37 Gravel Island	57	Canmar Explorer II
15	GLOMAR Beaufort Sea #1 CIDS	36	Pool Arctic #5, Tern Gravel Island	58	Canmar Explorer II
16	Spray Ice Island	37	Pool Arctic #5, Tern Gravel Island	59	Canmar Explorer II
17	Spray Ice Island	38	Brinkerhoff #84, Tern Gravel Island	60	GLOMAR Beaufort Sea #1
18	United Rig # 2, Mukluk Gravel Island	39	Brinkerhoff #84, Tern Gravel Island	61	GLOMAR Beaufort Sea #1
19	United Rig # 2, Mukluk Gravel Island	40	Brinkerhoff #84, Tern Gravel Island	62	SSDC/MAT
20	SSDC/MAT	41	Brinkerhoff #84, Tern Gravel Island	63	SSDC/MAT
21	SSDC/MAT	42	PAA #4 Tern Gravel/Ice Island	64	Beaudrill Kulluk
		43	PAA #4 Tern Gravel/Ice Island	65	Beaudrill Kulluk

Figure 3-2. Exploration Wells Drilled in the U.S. Arctic Ocean—From 1983 to 1991, exploration wells were drilled at 65 sites in the U.S. Arctic Ocean. Sixty of these were drilled in the Beaufort Sea in state and federal waters. Five exploration wells were drilled in the Chukchi Sea, all in federal waters farther from shore. A few of the Beaufort Sea exploration sites have resulted in production operations (see Figure 3-3), but there is no existing or planned production in the Chukchi Sea.



	Location	Operator	Oil Field	State/Federal	Status
#1	Oooguruk – Artificial Drilling Island	Pioneer	Oooguruk	State	In Production
#2	Near Spy Island – Artificial Drilling Island	ENI	Nikaitchuq	State	In Planning for 2011 Start-Up
#3	Northstar – Artificial Drilling Island	BP	Northstar	State/Federal	In Production
#4	Endicott Main Production Island (MPI)	BP	Duck Island	State	In Production
#5	Endicott Satellite Drilling Island (SDI)	BP	Duck Island	State	In Production
#6	Endicott SDI Expansion	BP	Liberty	Federal	In Construction

Figure 3-3. Existing and Near-Future Oil Production in the Beaufort Sea—Although there are a number of oil production operations on land in the U.S. Arctic (not shown on this map), there are only six existing or near-future oil production operations from subsea reservoirs in the U.S. Arctic Ocean, all in the Beaufort Sea. All production is conducted from artificial gravel islands.

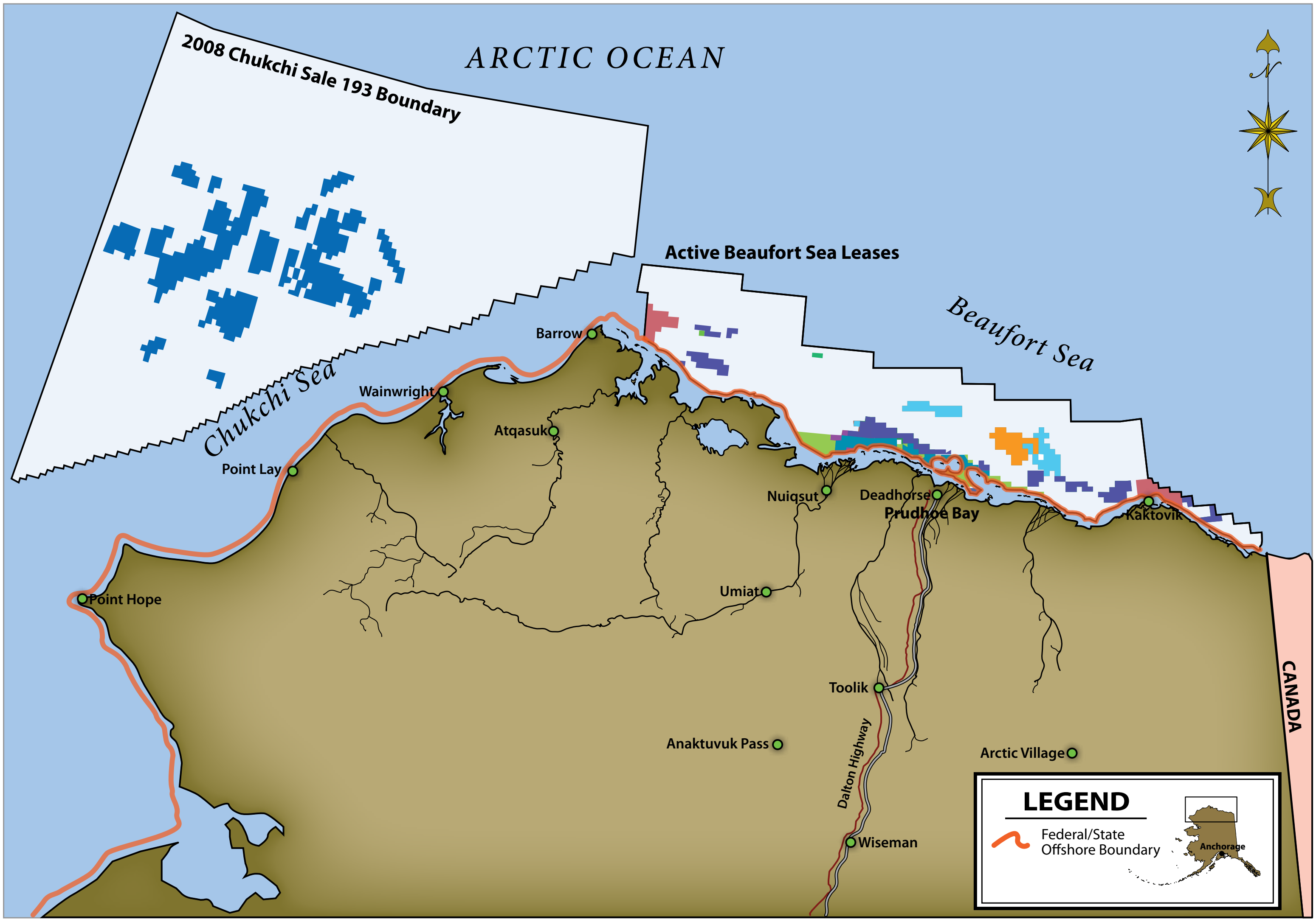


Figure 3-4. Map of Active Lease Areas in Arctic OCS *(Chukchi and Beaufort Seas).*

3.2 Oil Exploration and Production Operations

This section describes the basic mechanics of oil exploration (test drilling into a formation to determine whether the petroleum resources in that formation are viable to extract) and production (drilling into a previously tested or explored reservoir to bring oil to the surface for processing, storage and transport).

Exploratory drilling and subsequent oil production may be conducted from land, concrete drilling islands or water. Drilling configurations differ depending upon their location. For drilling in Arctic waters, the water depth, seasonal ice conditions and distance from land are all considerations. The discussion here focuses on drilling technologies for use in Arctic waters and explains how the Arctic marine environment can limit or impair drilling operations.

3.2.1 Exploratory Drilling

Exploratory drilling rigs use diesel engines to generate power to turn a drill bit, which cuts through the surface and the rock beneath with the help of hydraulic nozzles that spray large volumes of drill fluids pumped down from the surface. As the well bore is extended, the hole is periodically cased with metal pipe (known as casing) inserted into the borehole and cemented into place.

Drilling fluids, known as drilling mud, are pumped down the center of the drill string, which refers to sections of pipe that are added as the bit descends. The drilling fluid, which lubricates the drill string, removes the cuttings and holds back formation pressure, returns to the surface in the annular space between the drill string and the casing or borehole for cleaning and reuse. The hydrostatic weight of the drilling mud is the first barrier to prevent any oil or gas in the formation from intruding into the well.

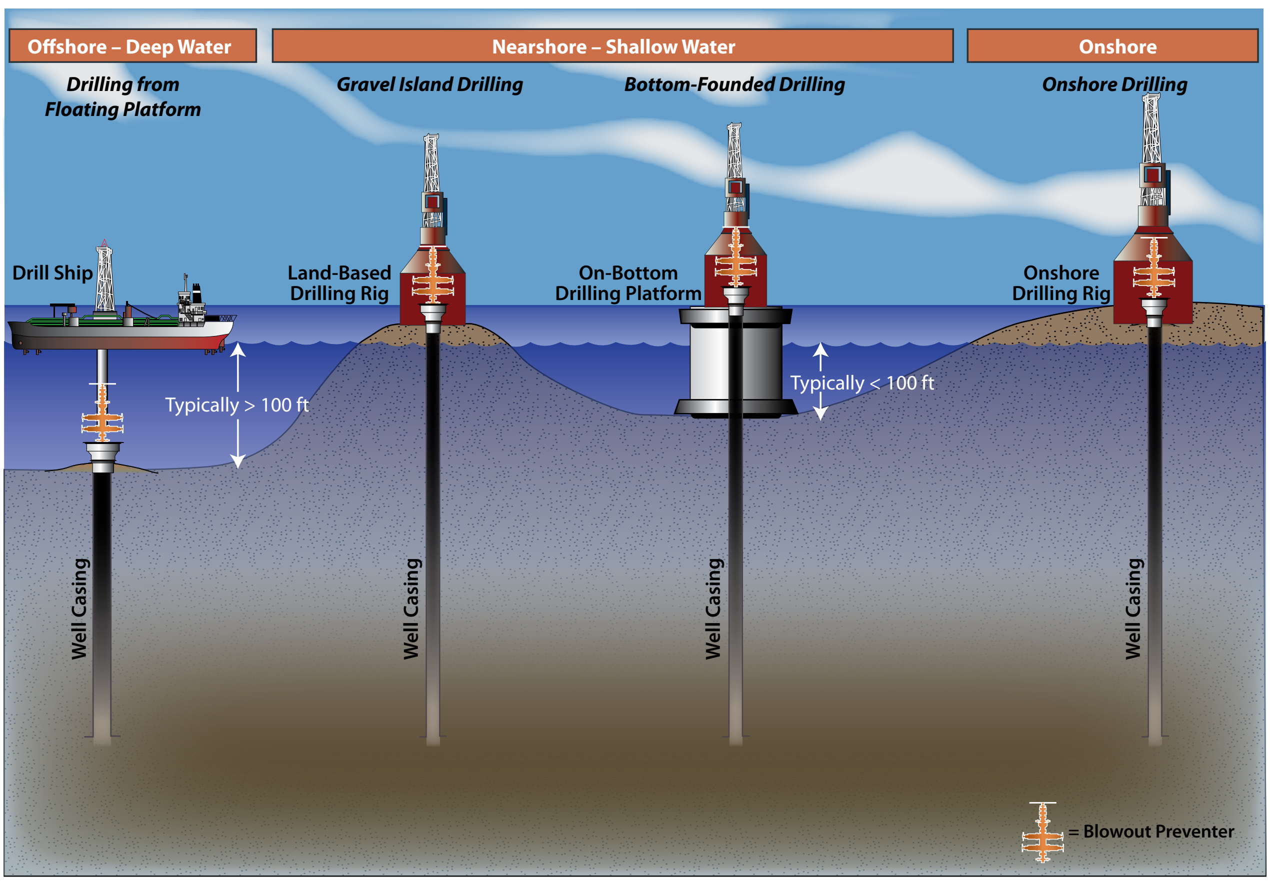
Drilling engineers design drilling mud systems with sufficient weight to control the subsurface pressure expected for the oil reservoir, but it is not always possible to predict the exact magnitude of the subsurface pressure, especially when drilling an exploration well in a previously unexplored area (NRC 2003b).

If the subsurface pressure exceeds the pressure imposed by the column of drilling mud in the well bore, the reservoir formation fluids (e.g., oil and gas) will flow into the well bore in what is known as a kick. A kick can eventually flow to the surface, potentially causing a blowout (an uncontrolled flow of oil and gas from the well). To prevent a kick from becoming a blowout, drilling rigs are equipped with heavy-duty valve assemblies called blowout preventers (BOP) attached to metal casing cemented into the well bore. Properly designed blowout prevention systems should control excess pressure at the wellhead, but under-designed or malfunctioning systems may fail to contain the excess pressure, resulting in a release of drilling mud and hydrocarbons.

Three types of structures have been used to support Arctic exploratory drilling in the United States and other countries: (1) artificial islands constructed of gravel or spray ice (winter only); (2) bottom founded or gravity-based platforms such as the Concrete Island Drilling Structure (CIDS); and (3) floating drill ships (Masterson *et al.* 1991)[3]. Artificial islands and bottom-founded drill structures are generally used in shallow waters (less than 75 feet). Bottom-founded or gravity-based platforms are massive, dense structures anchored to the ocean bottom by a concrete base with wells drilled through it. Bottom-founded drilling is usually limited to water depths of 100 feet or less, but work is underway to engineer deeper structures. Drill ships can work in water depths up to thousands of feet (Paulin *et al*. 2010, Matskevitch 2007). Figure 3-5 shows examples of drilling configurations.

One important difference between bottom-founded drilling structures and floating drill ships is the location of the blowout preventers. In the bottom-founded structures, the blowout preventers are located above water in an accessible location. In floating drilling operations, the subsea blowout preventer is located on the seafloor and can be accessed only with divers or remotely operated vehicles. Subsea blowout preventers are more complicated to activate and harder to inspect and test. In the event of a blowout, subsea blowout preventers are more difficult to access and control.

Figure 3-5. Various Exploratory Drilling Configurations—The blowout preventer sitting on the sea floor was the type used with the Deepwater Horizon.



3 Note that Masterson *et al.* 1991 also discuss jack-up rigs, which are mobile rigs that balance on the sea floor by resting on support legs and can be used in water depths up to 500 feet but are not generally suited for ice-infested waters. Masterson notes that jack-up rigs may be ice-reinforced and adapted for Arctic use in the future, but this has not occurred.

From the late 1970s to the early 1990s, 65 exploration wells were drilled in the U.S. Arctic Ocean—53 in federal waters and 12 in state waters—most in water depths of less than 72 feet and most conducted using bottom-founded drilling structures. A total of 15 exploration wells were drilled in the U.S. Arctic OCS during this period, at depths ranging from 60 to 220 feet (Table 3-1, Keener and Allan 2009).

Drilling was restricted to ice-free periods, which in the Beaufort is typically August to October and in the Chukchi is July to October. During the 1985 drilling season, Unocal and Shell and other minor partners drilled the first well in the U.S. Arctic from a floating drill ship, the Kulluk (Figure 3-6). This operation involved towing the Kulluk to the site in the fall and leaving the drill ship and its support fleet, unmanned, at an anchorage over the winter ice season so they would be on site when the spring breakup occurred (Gaida *et al*. 1983, Keener and Allan 2009).

As interest in Arctic oil exploration has increased, some work has been done to develop models for new drill ships built for Arctic service. Although no new drill ships have been constructed, naval engineers have proposed an Arctic class of drill ships with hull standards and propulsion design similar to other Arctic icebreaking vessels, combined with enhanced blowout prevention systems and a higher degree of self-sufficiency so that less frequent resupply would be required (Allan *et al*. 2009, Keener and Allan 2009, Masterson *et al*. 1991, Regg and Kuranel 1992).

Table 3-1. Exploration Wells Drilled in the U.S. Arctic Ocean, 1970s-1990s *(Keener & Allan 2009)*.

Drill Ship	U.S. Beaufort Sea	Chukchi Sea	Totals
Kulluk	5	0	5
Canmar/Dome Drill Ships	4	5	9
Barges	1	0	1
TOTALS	10	5	15

Figure 3-6. The Kulluk Drill Ship—The Kulluk, built in 1983, was the first floating drilling unit constructed for Arctic waters. The Kulluk drilled 12 wells in the U.S. and Canadian Arctic Ocean in the 1980s and 1990s. The Kulluk was purchased by Shell in 2005 and refurbished to support planned OCS drilling in the U.S. Arctic Ocean beginning in 2010. A major change to the Kulluk was the addition of thrusters, changing the drill ship from a barge that required towing to a self-propelled vessel.

3.2.2 Oil Production

Once an oil well has been drilled, it must be completed so it can be placed in production. Additional metal casing is placed in the well bore and cemented in place, a process that stabilizes the well bore, prevents collapse and provides pressure control. Inside the casing, valves and piping are installed to control the well pressure and provide a conduit for hydrocarbons to flow to the surface. Production wells are often equipped with emergency shutoff valves (subsurface safety valves), which are installed down in the well bore; these valves close in a fail-safe position when excessive pressure is encountered in the well bore. Wellhead valves (surface safety valves) are also placed atop the well to control the well pressure and route the hydrocarbons from the wellhead into a nearby piping transportation or tank storage system. Surface wellhead systems are commonly referred to as the "Christmas tree" assembly on a production wellhead, because the piping and valve assembly required to control the wellhead pressure is shaped like a tree and is adorned with valves and gauges to monitor and control the pressure. The surface safety valve is also designed to close if excessive pressure is observed at the wellhead or if a surface leak occurs, causing a sudden drop in pressure.

Oil production begins at the well. Each well produces oil, gas and water in varying proportions. Flow lines carry this three-phase mixture to a processing center, which contains a variety of equipment, including machines that separate the oil from produced water and gas, and equipment to condition the gas. Oil is filtered to remove sediment and is then considered to be sales grade and ready for transport to market. In the U.S. Arctic, oil produced from North Slope wells is routed through a crude oil transmission pipeline that carries it to the Trans-Alaska Pipeline System (TAPS), which transports the crude oil 800 miles south to the Valdez Marine Terminal for shipment to refineries in the United States and, occasionally, Asia. Natural gas is processed to remove liquids, then compressed and re-injected into the reservoir or used as a fuel supply for production operations. Produced water (water that is extracted from the well along with the oil and gas) is chemically treated and also injected into the reservoir. The re-injected gas and water help to maintain reservoir pressure (NRC 2003b).

All oil production in the U.S. Arctic Ocean takes place in state and federal waters of the Beaufort Sea (Figure 3-3) from bottom-founded structures based on artificial islands (Figure 3-7). As with exploratory drilling, production from bottom-founded structures typically occurs in areas where the water depth is less than 75 feet.

Figure 3-7. Example of Gravel Island-Based Production in Prudhoe Bay *(Photo Credits: BP)*—The Northstar Unit (left), operated by BP, produces from state and federal waters in the Beaufort Sea. The drilling operations are conducted from a five-acre man-made gravel island about six miles offshore. Endicott Island (right) is also a man-made island, 45 acres in size, and is in state waters 2.5 miles offshore. Northstar operates under seasonal drilling restrictions. Drilling is allowed during winter months, when the island is engulfed in shore-fast ice, and is prohibited during broken-ice periods. However, production from existing wells continues year-round.

Until recently, bottom-founded production was not considered feasible when water depth exceeded 75 to 80 feet (Masterson *et al.* 1991), although new gravity-based designs allow production in water depths of up to 250 feet (Hoff *et al.* 1994, Matskevitch 2007). If oil production were to commence in the U.S. Arctic Ocean in areas where water depths were above the 75- to 80-foot threshold, the production operations would require some adaptation of those typically used for offshore production in temperate regions: 1) a subsea completion and tieback to a shore-based processing center; 2) a gravity-based (bottom-founded) structure; or 3) a floating production, storage and off-loading facility. None of these types of structures have been constructed or tested in the deeper areas of the U.S. Arctic Ocean.

In a subsea completion, wellheads are located on the seafloor, manifolded together, and the produced oil/water/gas is piped directly to an onshore processing center. Subsea completions are not easily accessed to test or repair once the drilling rig has moved from the location.

Gravity-based production operations produce oil from subsea wells through the bottom-founded concrete structure, and oil is processed and stored onboard. Produced oil would probably be transported from the structure via subsea pipeline. A gravity-based structure in the U.S. Arctic Ocean would have to be constructed to withstand millions of tons of moving ice.

3.3 Challenges to Oil Exploration and Production in the Arctic Ocean

Exploration or production from floating structures in the Arctic Ocean, which would be conducted during the brief Arctic summer, must still overcome a number of obstacles.

3.3.1 Seasonal Ice

The short open-water season compresses the exploratory drilling season for operators using a drill ship. Even during the summer, ice floes may be encountered, making it necessary for floating operations to have some contingency for dealing with unexpected or encroaching ice. Ice management strategies must be able to handle first-year ice and must be prepared to deal with multiyear ice, should it encroach on drilling or production sites (Keener and Allan 2009, Hinkel *et al.* 1988).

During the frozen winter, the drill ship and associated support vessels must either be moved off site or closed in and left on site. Any equipment left over the winter must be ice class and able to withstand severe icing and tolerate temperatures to minus 40 degrees Fahrenheit. Ice can scour[4] subsea wellheads or pipelines in shallower water, requiring an extra level of precaution to prevent ice scours from damaging wells. Drill ships, floating processors and associated vessels will need to be able to overwinter in an emergency, in case ice conditions cause them to be iced in before they can be moved out of the region (Keener and Allan 2009).

4 Ice scouring, sometimes referred to as ice gouging, occurs when collisions between fast (moving) ice and pack ice create physical abrasions along the seafloor.

During the exploratory drilling in the Arctic OCS in the 1980s and 1990s, several wells took two seasons to complete. Reasons for the delays included ice conditions in the Beaufort and heavy weather in the Chukchi. Whale migration also caused a suspension of drilling activities because of permit requirements imposed on the drilling companies. In an article documenting past exploration activities in the Arctic OCS, Regg and Kuranel (1992) describe challenges encountered during the 1991 drilling season:

> *"In 1991, severe ice was responsible for delaying the start of drilling operations in the eastern Beaufort Sea until mid-September. This shortened the already limited drilling season to roughly 30 days. Chukchi Sea operations were initiated earlier (mid-July), but were continuously plagued by hazardous ice floes moving through the area and occasional heavy weather causing excessive vessel motion."*

3.3.2 Extreme Storms

Severe storms are common in the fall and early winter in the U.S. Arctic Ocean and may overlap with the end of drilling season for floating offshore production; global climate change may exacerbate the frequency or intensity of these storms (IARC 2015). During the months when the Arctic Ocean is ice-free, high winds and storms may drive higher sea states, with wave heights approaching 30 feet.

3.3.3 Infrastructure and Logistics

Logistical challenges of the U.S. Arctic Ocean necessitate self-sufficiency because of limited support and infrastructure in many areas. All of the equipment required for exploratory drilling and production—well casings, drill strings, mud, cement, diesel fuel and associated drilling equipment, as well as the people required to operate this equipment—must be transported to the drilling site by air, land or sea. In the Arctic OCS, the basic logistics associated with supporting floating production are complicated by a lack of transportation infrastructure (NRC 2003b).

A shift from exploration to production in the OCS will require development of waste-disposal and water treatment programs (and possibly facilities), transportation of power generation sources, construction of additional infrastructure, and establishment of residential facilities for production workers. Logistical support requirements for the life cycle of an oil production facility are substantial, including on- and off-road vehicles, aircraft (fixed and rotary wing), vessels of various types and sizes, and trained personnel. The ecological footprint of all these activities is significant, and in addition to the risk from oil spills, exploration and production activities also affect air and water quality (NRC 2003b).

Oil exploration activities in the Beaufort Sea are concentrated during the winter season, because the logistical requirements of drilling activities are more easily met during the winter by building ice roads, pads and ice airstrips. A shift to floating exploration or production operations, which would be focused during the summer months, will require the development of new transportation methods and corridors and has the potential to be more environmentally damaging (NRC 2003b).

In either season, transportation of the equipment and personnel required to undertake exploratory drilling operations farther from the shoreline or in new regions of the Chukchi Sea will require significant effort and planning (e.g., Figure 3-8).

Figure 3-8. The U.S. Coast Guard Launching a Vessel in the Shallow Waters Near Barrow, Alaska *(Photo Credit: U.S. Coast Guard).*

3.4 Potential for Blowouts and Oil Spills from Exploration and Production in the U.S. Arctic Ocean

Oil spills may occur during any phase of oil exploration, production, storage or transportation. Potential sources of marine oil spills include well blowouts during subsea exploration or production, leaks from subsea pipelines, spills from on-land storage tanks or pipelines that travel to water, or vessels carrying oil either as fuel or cargo. Oil spills may be caused by a variety of factors, such as human error, structural or mechanical failures or sabotage. Arctic conditions such as sea ice, low temperatures, reduced visibility or complete darkness, high winds and seas, and extreme storms add to the probability of an accident or error that might cause a spill (Anderson and Talley 1995, MMS 2007b).

3.4.1 Well Blowouts

An oil well blowout may occur at the surface or on the seafloor. Surface blowouts deposit oil on the surface of the water, sea ice, drilling platform or other adjacent features. A subsea oil well blowout, such as the Deepwater Horizon incident, involves an underwater release in which oil and gas travel upward through the water column before reaching the ocean's surface. Depending upon the sea ice formations present when a blowout occurs, the oil may be trapped below the ice, may be incorporated into newly forming ice or may spread between ice floes.

An uncontrolled oil well blowout creates the largest possible oil spill risk if the oil reservoir pressure is high enough to force the oil to flow to the surface. Unlike a spill from a tank or pipeline, a well blowout has a much larger potential volume, depending upon the size and pressure of the oil reservoir. Blowouts that occur during exploratory operations may be particularly high in volume because the pressures within subsurface reservoirs may not be known. The Deepwater Horizon blowout, the largest well blowout worldwide, occurred during exploration drilling, as did the 2009 Montara well blowout in Australia's East Timor Sea (Figure 3-9).

Figure 3-9. Major Well Blowouts—*(Photo Credits, top, Chris Twomey/Environs Kimberley; bottom, NOAA)* In August 2009, the Montara platform (top) experienced a blowout during exploratory drilling in the EastTimor Sea, Australia. Thirty years earlier, the second-largest well blowout (after the Deepwater Horizon)occurred from the Ixtoc I in Mexico, also from an exploratory well (bottom). Both blowouts were controlledby drilling relief wells; the Montara relief well required 10 weeks to complete, and the Ixtoc I required nine months.

Despite their infrequency, blowouts are still a threat during both exploration and production. Although most blowouts do not lead to a major oil spill, they occur every year. From 1992 to 2006, the rate in the United States was one blowout for every 387 wells drilled, for 39 total blowouts through the end of the 1990s (Fairweather 2000). The Deepwater Horizon spill occurred in unusually deep water, but a 2007 MMS study showed that most blowouts occur in water depths of less than 500 feet (Fairweather 2000). Several other major oil well blowouts worldwide illustrate this risk (Table 3-2). In addition to the environmental damage, Table 3-2 shows that more than 230 lives have been lost because of well blowouts.

Data on oil well blowouts in the Arctic Ocean is limited because oil exploration and production have been limited in the Arctic OCS. In Alaska's Arctic, 11 well control incidents were documented from 1977 to 2000 in which natural gas and/or drilling muds were released to the environment (Fairweather 2000).

Table 3-2. Alphabetical List of Major Well Blowouts Through 2010 (Source: Oil Rig Disasters 2010, ADN 2008)—Though infrequent, well blowouts do occur. A review of major well blowouts worldwide shows that at least one blowout has occurred in most years since the mid-1970s. In the past decade alone, 16 well blowouts have been documented worldwide, two of which resulted in a major oil spill. Well blowouts resulting in reported oil spills are shaded in gray; blowouts that occurred in the United States are shown in bold text. *Key: DS—Drill Ship, JU—Jack-Up Rig, LR—Land Rig, P—Platform, SS—Semi-Submersible, S—Ship

Rig Name / Well name	Year	Location	Spill Size	Rig Type*	Comments
Actinia	1993	Vietnam		SS	Major release
Adriatic IV	2004	Mediterranean Sea, Egypt		JU	Fire destroyed rig and platform; gas blowout
Al Baz	1989	Nigeria		JU	Burned and sank, five fatalities
Arabdrill 19	2002	Saudi Arabia		JU	Fire destroyed rig and platform
Atlantic No. 3	1948	Alberta, Canada		LR	Major release, fire; blowout lasted six months
Banjar Panji-1	2006	Java, Indonesia		LR	Mud volcano, major release
Beaver Creek 1A	**1967**	**Cook Inlet**		**n/a**	**Gas to surface**
Beluga River 212-35	**1962**	**Cook Inlet**		**n/a**	**Gas to surface**
Blake IV/Greenhill	1992	Gulf of Mexico	72,000 to 112,000 gal.	JU	Major release, fire
Bohai 3	1980	—		JU	Fire, 70 fatalities
Cerveza	1983	—		P	Abandon
Cirque No. 1	**1992**	**North Slope**		**n/a**	**Gas to surface during exploratory drilling**
Cook Inlet State No. 1	**1962**	**Cook Inlet**		**n/a**	**Gas to surface, exploration well**
C.P. Baker	1964	Gulf of Mexico		DS	Catamaran type, explosion and fire, 22 fatalities
CPF1-23	**1979**	**Kuparuk Field**		**n/a**	**Gas to surface**
Deepwater Horizon	**2010**	**Gulf of Mexico**	**4,900,000 bbl**		**Three months required to control blowout; five months to complete relief well**
Drake Point L-67	1969	Canadian Arctic		LR	Ice volcano
Ekofisk B	1977	Norwegian CS	202,000 bbl	P	Major release
Enchova Central	1984	Enchova Field, Brazil		P	Fire, lifeboat fell to sea, 37 fatalities
Enchova Central	1988	Enchova Field, Brazil		P	Destroyed by fire
Ensco 51	2001	Gulf of Mexico		JU	Setting casing string, fire
F-20	**1986**	**Prudhoe Bay**		**n/a**	**Gas to surface**
Funiwa Platform	1980	Nigeria	200,000 bbl	P	Major release; 14 days to control blowout
Glomar Baltic I	2001	Gulf of Mexico		JU	—
Glomar Grand Isle	1983	Indonesia		DS	Fire
Grayling Platform (Trading Bay Unit)	**1985**	**Cook Inlet, Alaska**		**P**	**Gas to surface**
Gubik #2	**1951**	**Umita, Alaska**		**n/a**	**Gas to surface during exploration drilling**
Hasbah Platform	1980	Persian Gulf	100,000 bbl	P	Major release, 19 fatalities

Rig Name / Well name	Year	Location	Spill Size	Rig Type*	Comments
I-23/Q-20	**1994**	**Endicott, North Slope**		**n/a**	**Gas to surface**
Ixtoc-1	1979	Mexico	3,500,000 bbl	JU	Nine months to cap well
Jim Cunningham	2004	Egypt		SS	Fire
J-23	**1987**	**Prudhoe Bay**		**n/a**	**Gas to surface**
Kavik #1	**1969**	**North Slope**		**n/a**	**Gas to surface during exploration drilling**
Keyes Marine 303	**1990**	**Gulf of Mexico**		**JU**	**—**
King Christian D18	1970	Canadian Arctic		LR	Ice volcano
Little Bob	1968	—		JU	Fire off La. Coral Drilling, seven fatalities
Lodgepole	1982	Alberta, Canada		LR	Amoco, major H2S release, two fatalities
Lusi Mud Volcano	2006	Java, Indonesia		LR	Mud volcano, major release
Maersk Endurer	1980	Gulf of Suez		JU	Derrick collapse, renamed EDC Setty, estimated three fatalities
Maersk Giant	2006	Norwegian CS		JU	Shallow gas
Marine IV	**2001**	**Gulf of Mexico**		**JU**	**—**
MGS State 17595 No. 1	**1962**	**Cook Inlet**		**n/a**	**Gas to surface, exploration well**
Mississippi Canyon 311A	**1987**	**Gulf of Mexico**		**P**	**Platform tilted**
Mobil Moquawkie No. 1	**1965**	**Cook Inlet**		**n/a**	**Gas to surface, exploration well**
Moquawkie No. 4	**2008**	**Cook Inlet**		**n/a**	**Gas to surface**
Mr. Louie	1963	German CS		JU	Crater
Montara/West Atlas	2009	Timor Sea, Australia	30,000-220,000 bbl	JU	Major spill; size estimates vary greatly; 74 days to drill relief well
NFX Platform A	**1999**	**Gulf of Mexico**		**P**	**Fire**
NGI-7	**1976**	**Prudhoe Bay**		**n/a**	**Gas to surface**
Ocean King	**2002**	**Gulf of Mexico**		**JU**	**Fire**
Ocean Odyssey	1988	UK CS		SS	Fire, one fatality
Penrod 52	**1983**	**Gulf of Mexico**		**JU**	**Collapsed during blowout**
Petrobras P7	2001	Bicudo Field, Brazil		P	Fire
Petromar V	1981	South China Sea		DS	Sank after blowout
Placid L10a	1983	SNS, NL		P	Corrosion
Pride 1001E	**1997**	**Gulf of Mexico**		**P**	**Fire**
Ron Tappmeyer	1980	Saudi Arabia		JU	Hasbah platform blowout, 19 fatalities
Saipem Paguro	1965	Off Ravena, Italy		JU	Destroyed by fire
Sea Quest	1980	Nigeria		SS	Sedco 135C, fire, scuttled off Nigeria
Sedco 135F	1979	Mexico		JU	IXTOC 1—Capped 1980 Mar 23
Sedco 252	1989	Indian Coast		JU	Fire, three fatalities
Ship Shoal 246b	**1980**	**Gulf of Mexico**		**P**	**Killed after one day**
Simpson Core Test #16	**1948**	**North Slope**		**n/a**	**Gas to surface while drilling exploration well**
Simpson Core Test #26	**1950**	**North Slope**	**n/a**	**n/a**	**Oil release to surface while drilling exploration well**
Snorre A	2004	Norwegian CS		P	Seabed gas blowout

Rig Name / Well name	Year	Location	Spill Size	Rig Type*	Comments
South Timbalier 26	**1970**	**Gulf of Mexico**		**P**	**Platform lost, four fatalities**
Steelhead Platform	1987	Cook Inlet, Alaska		P	Fire. Unocal, Penrod rig also lost, nine months to complete relief well
Sundowner 15	1996	Gulf of Mexico		P	Fire
Teledyne Movible 16	1989	Gulf of Mexico		JU	Total loss
Treasure Seeker	1984	Norwegian CS		SS	Shallow gas
Trinimar Marine W327	1973	Venezuela		P	Major release
Union Oil Platform A	**1969**	**Dos Cuadras F, U.S. OCS**	**80,000 to 100,000 bbl**	**P**	**Major release, 11 days to control blowout; spill estimated at 80,000 to 100,000 bbl**
Usumacinta	**2007**	**Gulf of Mexico**		**JU**	**Storm, major release, 22 fatalities**
Viking Explorer	1988	SE Borneo		DS	Explosion and sinking. Total Oil, four fatalities
Vinland	1984	Sable Island, N. Atlantic		SS	Shell, Uniacke G-72
West Vanguard	1985	Haltenbanken, Norway		SS	One fatality
Zacateca	1986	Mexico		JU	Sank. Perforadora Co
Yum II / Zapoteca	1987	Gulf of Mexico		JU	PEMEX
Zapata Enterprize	1985	Javan coast		JU	Fire
Zapata Lexington	**1984**	**Gulf of Mexico**		**JU**	**Fire, four fatalities**
Zapata Topper III	**1975**	**Gulf of Mexico**		**JU**	**Sank off La.**

The potential oil spill volume from a blowout is equal to the volume of the reservoir that can flow to the surface until the well is controlled. Oil reservoirs may contain billions of barrels of oil and may continue to spill into the environment until the well naturally bridges on its own (plugs with sand or debris); until the well is controlled by human or mechanical intervention (e.g. capping the well, igniting the well, drilling a relief well); or until the subsurface reservoir pressure finally drops to such a level that the oil stops flowing out. Although blowouts are very infrequent, they can last for days, weeks or months.

Engineers design drilling operations and manage drilling fluids to reduce the risk of a blowout. Drilling fluid systems and blowout prevention systems are critical safety factors, particularly during exploratory drilling, when unexpected reservoir pressures may be encountered.

3.4.2 Other Spills from Oil Production Operations

Oil spill risks from production operations tend to increase with the age of the equipment. As oil reservoirs age, the balance of fluids extracted may change, with a higher ratio of produced water to produced oil, a combination that is typically more corrosive. Valves and piping may eventually corrode or erode and face a higher risk of failure or leakage. Saltwater can also corrode pipelines and oil production equipment from the outside in. Routine maintenance, inspection, repair and replacement programs help to reduce the risk of oil spills from production operations, but they never eliminate the risks. There may also be a tendency toward complacency in older production operations, a factor that can contribute to the risk of an accident or oil spill.

As discussed in Section 3.4.1, a catastrophic blowout from a producing well would be the worst-case discharge during production, but several other sources could also cause a damaging spill. Any subsea pipeline used to transport oil from production wells to onshore facilities could experience a sudden breach that results in a rapid discharge of the pipeline contents. Small, undetected leaks from subsea pipelines can also be extremely damaging if they continue undetected for long periods. Significant amounts of undetected oil can be spilled from pipeline leaks, as occurred in the largest oil spill from Alaska's North Slope production operations in March 2006. In that incident, more than 200,000 gallons of crude oil was released to the environment onshore through a chronic leak that went undetected for several days (Alaska Department of Environmental Conservation 2006).

A release from a subsea pipeline that occurs when sea ice is present may spread under the ice or within ice floes or become incorporated into newly forming ice. A pipeline release at or above the waterline or a spill on land that travels to the water would discharge oil to the sea surface.

It is critical that pipelines are designed with materials that are appropriate for the environment and length of expected service. Offshore pipelines experience higher external corrosion rates (saltwater exposure), have higher potential to harm the fragile offshore environment, are typically hard to access during most of the year (e.g., buried subsea or under ice) and are more difficult to inspect and repair. Pipelines installed in ice-laden waters must be properly designed and constructed with double walls, and in some cases it is necessary to bury the pipeline well below the seabed or protect the pipeline with a thick cement casing to avoid ice scouring. Pipelines must be protected from internal and external corrosion and erosive forces and should undergo routine maintenance, inspection, repair and replacement programs to ensure their integrity.

In addition to spillage from transmission pipelines, oil may be spilled from storage tanks, facility piping or manifold valve systems on offshore platforms, or from onshore storage tanks required along the pipeline route. The potential worst-case oil spill volume would be the volume of the tank or tanks or the volume of oil in the piping. The amount of oil discharged to the water depends on how much escapes secondary containment around the tanks and piping, and how quickly the leak is controlled. Spills from tanks associated with offshore platforms may flow directly to the water or sea ice surface because these tanks typically have no additional containment around them. Prevention systems for offshore storage tanks and piping may include use of double-walled piping, double-walled storage tanks and improved containment structures to capture and pump recovered fluids before they reach water.

Increased vessel traffic associated with oil production may also present additional spill risks. Oil tankers or barges pose a spill risk during oil transfer operations and while in transit. The potential spill volume from a tanker or other vessel ranges from a small spill during oil transfer to a complete cargo loss. Vessel spills pose an additional response challenge because they can occur anywhere along the vessel route. A vessel spill may release hydrocarbons above or below the sea surface, depending upon where the tank breach is located.

Spill prevention measures for tankers and other vessels may include structural features such as double hulls or double bottoms. Engineered systems that detect leaks or ice or monitor weather can also increase onboard safety. Navigational safety programs such as vessel traffic systems, navigational restrictions during periods of adverse weather, and monitoring of vessel traffic may help to prevent accidents. Prevention measures that target human factors—the human or organizational errors that are estimated to cause as much as 85 percent of marine vessel accidents—are also important. These may include personnel training, drug and alcohol testing, medical monitoring, and watch-standing procedures that ensure adequate crew rest (U.S. Coast Guard 1998).

4 IMPACT OF OIL SPILLS ON ARCTIC ENVIRONMENT AND ECOLOGY

A 2007 Arctic Council study of potential effects of oil and gas in the Arctic found that oil and gas activities in this sensitive region are likely to increase, including expansion into new areas and extension of transportation systems (AMAP 2008b). The U.S. Arctic Research Commission echoed these concerns in its white paper with recommendations for research on oil spills (U.S. Arctic Research Commission 2010). As this expansion progresses, oil spills "have the greatest potential to impact aquatic environments," the commission said (AMAP 2008b).

To avoid harm to the ecosystem and its many threatened and endangered species (Table 4-2), oil and gas operations in the Alaskan Arctic Ocean must be carefully designed to take into account both the behavior of spilled oil in regions with sea ice present during part or all of the year, and the unique vulnerabilities of the Arctic ecosystem to spilled oil (Figure 4-1). This chapter describes the fate and effect of oil spilled in the Arctic marine environment and describes the vulnerabilities of Arctic species and ecosystems to the spilled oil, and the potential short- and long-term impact of oil spilled in the offshore Arctic.

Figure 4-1. Open Lead Near Point Hope, Alaska *(Photo Credit: Henry Huntington)*—The U.S. Arctic Ocean and its coastline have unique vulnerabilities to oil spills that should be factored into the decision-making process for new exploration or production.

4.1 Fate and Behavior of Oil Spilled in Arctic Waters

4.1.1 Weathering and Emulsification

When oil is spilled on water, it begins to weather and change. The presence and formation of sea ice can affect oil weathering in many ways. Observations from actual spills, laboratory experiments

(Photo credit: North slope. *Ground Truth Trekking, 2010*) and field studies provide some insight into oil and ice interactions. This interaction is heavily influenced by where the oil is released: above or below the ice (Dickins and Fleet Technology 1992).

Oil behavior and movement in ice conditions may differ from those exhibited in ice-free waters. For example, spilled oil may not spread as far in the presence of ice floes or irregularities on the ice surface, because the ice may create natural barricades to oil movement (Evers et al. 2004). Oil can move hundreds of miles from the spill site, however, if it is trapped under or within a piece of ice (Wilson and Mackay 1987, NRC 2003a).

The behavior, fate and weathering of oil spilled in Arctic waters are affected by multiple factors, including the type of oil; the temperature of the oil and water; and the wind, current, tides and weather. The presence of sea ice and low ambient temperatures will slow the weathering process and also affect spreading and other physical processes (Table 4-1). If the oil is frozen or trapped in the ice, the weathering process may stall until the oil is thawed and exposed to air and water. Sea ice slows the process of water uptake and evaporation (Dickins and Fleet Technology 1992, Evers et al. 2004). Evaporation will be slowed by cold weather and may be completely arrested if the oil is buried in snow or ice (Singsaas 2005). If the type of oil and the presence of waves lead to emulsification, the volume of the oil-water mixture will increase the size of the slick, and other weathering processes will slow (NRC 2003a).

Table 4-1. Oil Weathering Processes Affected by Sea Ice *(adapted from Evers et al. 2004).*

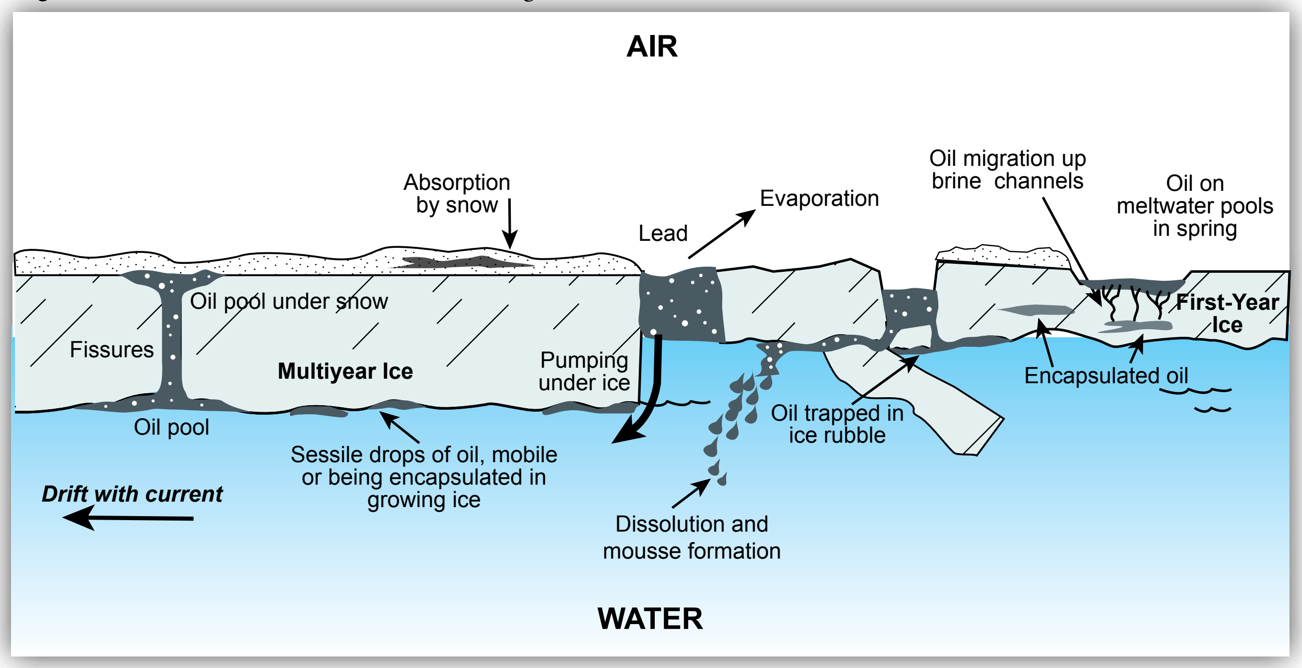
Process	Open Water	Extreme Cold or Ice
Spreading and Dispersion	A thick layer of oil grows thinner and covers a larger area of water (depending on the oil).	Ice acts as a physical barrier (broken ice) or retardant (grease ice); oil does not spread or disperse as far and ends up in a thicker layer.
Drift	Oil moves with wind/current.	Oil will drift separately from the ice at less than 30 percent ice coverage, and with the ice at 60 to 70 percent (or greater) coverage. Unpredictable in broken ice conditions.
Evaporation	Relatively fast (thin oil films).	Slower where oil spills are thickened.
Emulsification	Higher in areas with breaking waves. Rate of emulsification, total water uptake, and stability of emulsion depend on type of oil.	Total water uptake and rate of uptake may be lower as a result of reduced wave activity because of the presence of ice.

4.1.2 Oil-Ice Interactions

The fate and behavior of oil spilled into ice-infested waters depends to a large extent on the type of ice present and the timing of the release relevant to the ice formation and breakup cycle (Figure 2-4). Oil may move above or below the ice or become trapped within it (Figure 4-2).

If oil is released underneath a solid sheet of ice (e.g. from a subsea blowout or pipeline rupture), it will rise until it reaches the ice cover, then spread laterally and accumulate in crevices under the ice. The rate of spreading is influenced by several factors, including the proportionate amount of gas, which tends to increase the spreading rate. The velocity of currents under the ice will also affect the spreading rate (Dickins and Fleet Technology 1992). The rough underside of the ice will cause the oil to pool in some places unless the current is strong enough to keep the oil moving (AMAP 1998). Late-winter ice tends to be rougher in texture and able to hold more oil pooling under its uneven surface. It is estimated that 1.5 million liters of oil per square kilometer (km^2) could be stored under late-winter fast ice along the Alaska North Slope (Dickins and Buist 1999). Oil spilled on top of a continuous ice sheet will tend to move based on the wind direction and velocity (Dickins and Fleet Technology 1992).

Figure 4-2. Oil-Ice Interactions *(Bobra and Fingas in AMAP 1998).*



The actual behavior of oil spilled to newly frozen ice (e.g., grease or slush ice, Figure 4-3) has been widely variable. Oil has been trapped at the edges of ice pancakes, frozen in place, caught within the structure of the grease ice, observed moving under the ice and dispersing as leads open, and carried underneath brash ice (Fingas and Hollebone 2003). Ice floes may transport oil hundreds of miles from the spill source. The slick can also move underneath ice floes (e.g., pancake ice in Figure 4-3) or be tossed on top of them in wave action, causing bumping and moving of the floes (Wilson and Mackay 1987). Some studies suggest that oil will move at the same rate and in the same direction as ice (Dickins and Buist 1999). Oil movement is more strongly influenced by the movement of ice at higher ice concentrations (Dickins and Fleet Technology 1992).

Oil trapped under multiyear ice could remain in the marine environment for many years (AMAP 1998) and may not be released until it slowly migrates to the surface. Some scientists estimate that oil could be trapped under multiyear ice for up to a decade (NRC 2003a). Oil spilled on the surface of an ice sheet tends to pool in ice depressions and may be trapped under snow cover. However, oil spilled on top of the ice surface will be exposed to the air and subject to evaporation (Owens *et al.* 2005).

Figure 4-3. Example of Ice Formations *(Photo credits: Mike Dunn/NOAA)*—Sea ice formation is a highly dynamic process, and the type of ice present when an oil spill occurs will affect the fate and behavior of the spilled oil. Oil spilled to newly frozen ice such as grease ice may move under the ice, migrate into openings in the ice or become encapsulated in the growing sheet. Oil released when ice has begun to form pancakes (right) may move under the ice pack or be tossed on top of it by wave action. As the ice sheet melts and breaks up, oil will be released back to the water. The level of emulsification will not change much while the oil is encapsulated.

Oil released during freeze-up or breakup will be impeded by grease or slush ice between the floes (Dickins and Fleet Technology 1992). Because of the density difference between oil and water, spilled oil probably will rise to the surface of a slushy oil and ice mix (Martin *et al.* in Fingas and Hollebone 2003). If a spill occurs during freeze-up when the ice sheet is still forming, oil may become encapsulated in the ice. A review of field tests and laboratory experiments finds that oil can be partially encapsulated within four hours and fully encapsulated in as little as 24 hours after contact with the ice (Fingas and Hollebone 2003). The oil essentially becomes part of the ice sheet and will move with the sheet.

Conversely, the oil can affect ice formation by acting as an insulator to slow ice formation or can speed it by reducing wave activity. The presence of oil will typically slow early ice development (Ross in Wilson and Mackay 1987). When oil and gas are released together, as in a well blowout, the gas may also affect the oil by causing fractures or heaving (Dome's Petroleum Ltd. in Fingas and Hollebone 2003).

Areas of open water such as ice leads and polynyas can change oil behavior as well. Polynyas and leads will allow oil to spread more rapidly than it would on the ice surface or below the ice, causing the oil to pool in those areas (Arctec in Wilson and Mackay 1987). The weathering process will resume once the oil is exposed to open water, air and wind in the polynyas and leads, unless it is encapsulated by freezing water conditions. Water moving in or out of a lead can cause a pumping action, which moves oil out from under ice and into the lead. This is particularly common in the early hours of the spill when the oil first encounters the ice (Reed et al. 1999).

Oil that is frozen in ice or transported with ice floes has the potential to end up on the shoreline, where the oil can mix with the sediment, form emulsions or cover beaches, depending on the type and amount of oil and how much it has weathered. Oil released under ice or encapsulated within it could reach the shoreline but be invisible until the ice begins to break up or melt (AMAP 1998).

When the spring melt starts, oil tends to move upward through the ice and form pools that will begin to weather and eventually be released to the water (AMAP 1998). As ice begins to melt, brine channels open up and may allow oil trapped in or under the ice to travel to the surface (Dickins and Fleet Technology 1992).

This process of releasing oil from within the ice will accelerate as spring temperatures rise, forming increasingly thicker pools. Fine droplets of oil, such as the spray released from an oil well blowout, may take more time to reach the surface than a thicker slick (Dickins and Buist 1999). The release of encapsulated oil during spring melt has been correlated to the time at which it becomes frozen into the ice. In general, the earlier the oil was encapsulated in the ice formation, the earlier the oil will be released in the spring. One study found that 85 percent of oil encapsulated into the ice sheet early in the fall was released to the surface before spring breakup. Encapsulated oil that has not emulsified tends to remain non-emulsified, and emulsified oil entrapped in ice tends to remain in its emulsified form (Dickins and Fleet Techonology 1992).

Microorganisms such as bacteria and some fungi slowly degrade petroleum hydrocarbons spilled in the marine environment (AMAP 1998). However, degradation is slower in coldwater areas than in temperate regions, because the oil tends to be more viscous and does not evaporate as quickly, making it less accessible to bacteria (Atlas 1985 in AMAP 1998).

4.1.3 Predicting the Fate of Oil in Sea Ice

Predicting the fate of oil in sea ice requires new and improved algorithms to take into account the seasonal variation, weathering and other factors, described above, that affect the behavior of oil spilled on, in or under ice. Standard models used to predict the fate of oil spilled in temperate marine waters are inadequate for modeling the fate of oil in dynamic sea ice conditions. Despite considerable research into the fate and behavior of oil in sea ice, little progress has been made in integrating this data into existing oil spill models.

A 2010 study considering the state of oil spill modeling in ice found:

> *"Modeling oil spills in ice-infested water is much less developed than oil spill modeling in open water. This is not necessarily due to the lack of quantitative understanding of the fate and behavior side. ... Overall, it appears that there is a lag between the advancement of understanding the fate and behavior and the integration of the results into operational oil spill models." (Khelifa 2010)*

The 2010 study, conducted by researchers at Environment Canada, found that existing modeling approaches that do include oil-in-ice interactions are more than two decades old and essentially use the same parameters as open-water oil spill models, with a correction factor that is meant to account for the presence of ice but is oversimplified and not technically accurate (Khelifa 2010). Upon reviewing theoretical models of oil behavior in ice conditions, Fingas and Hollebone (2003) conclude that the existing models are inadequate because most are tested only against laboratory or very small-scale field experiments and are unable to adequately replicate the complexity or uniqueness of different ice-ridden marine environments. Reed *et al.* (1999) concluded that the ice leads play a dominant role in oil behavior but are not incorporated in most models. It is especially challenging to develop accurate modeling algorithms to predict the behavior of oil in ice over time, because the characteristics of the oil are constantly changing, as are the ice conditions.

Predicting the fate of oil in the specific circumstances surrounding any incident, especially in an ice environment, is beyond the capacity of existing models. In fact, in current oil trajectory studies that have been completed for the offshore Alaska Arctic, ice conditions have been excluded entirely because of the inability of the National Ocean and Atmospheric Administration (NOAA) models to account for oil-ice interactions. To improve oil spill modeling capabilities in sea ice, models must be validated against data from Arctic oil spills or large-scale field trials. Because of the high variability of oil behavior in sea ice conditions, models developed for one region of the Arctic may require some adjustment before being applied to other Arctic regions. Data are available for only a limited range of oil and ice types (Singsaas and Reed 2006).

Understanding and predicting how oil and ice may interact in the offshore Arctic is only one component of assessing the potential impact of a major Arctic oil spill. Another equally important consideration is how oil spilled in different regions at different times of the year may affect the Arctic ecosystem.

4.1.4 Long-Term Fate of Oil Spilled in Cold-Water Environments

Follow-up studies of past oil spills, including the Exxon Valdez incident, have increased our understanding of the long-term consequences of oil spills in cold-water regions (AMAP 2008b).

A 2003 study on impacts of the Exxon Valdez spill found that although most of the oil on the beaches was removed in the first few years, oil remaining beyond that time was generally found in areas that were protected from physical weathering, and further degradation was very slow (Peterson *et al.* 2003). In 2005, Exxon Valdez oil was found only slightly weathered under beaches across the spill impact area (Integral Consulting Inc. 2006). The lingering oil remains toxic and biologically available, and scientists predict that this subsurface oil may persist for decades (Short *et al.* 2004).

A series of intentional oil spills was conducted during 1982 and 1983 on Canada's Baffin Island to study the impact of oil spilled in Arctic environments, focused primarily on shoreline cleanup technologies and shoreline impacts. Studies were conducted to evaluate the long-term fate of oil spilled on an Arctic shoreline and the toxic impacts of that oil. Much of the oil weathering documented on Baffin Island and in Prince William Sound was due to physical processes. Low temperatures, lack of sunlight and ice cover slow all forms of oil weathering—in addition to the slowing of bacterial degradation by cold weather—causing oil to linger in cold-water environments longer than in more temperate regions (AMAP 2002).

The long-term effects of oil spills have also been documented in Cape Cod, Mass., where recent studies published by the Woods Hole Oceanographic Institution found that oil remains in the sediment layer of some coastal marshes from a 1969 oil spill. The lingering oil continues to affect the behavior of burrowing fiddler crabs, which have been observed to avoid digging burrows into this oiled sediment layer. The crabs have also been observed to show signs of toxic effects from the 38-year-old oil (Culbertson *et al.* 2007).

4.2 Vulnerabilities of the Arctic Ecosystem to Oil Spill Impacts

The U.S. Arctic Ocean hosts a productive ecosystem and provides vital habitat to walruses, polar bears, ice-associated seals and whales, along with seabirds, fish and myriad smaller organisms that support a complex food web (Figure 4-4). Arctic species are well adapted to the area's conditions and are found nowhere else in the United States. Millions of birds and various species of whales migrate great distances to the Arctic each year. More than 100 species of fish—including Arctic cod, capelin, herring and saffron cod—underpin the region's marine food chain.

Ice is present in the Arctic Ocean for much of the year, and the interface between ice and water is the heart of the Arctic ecosystem. A spring bloom of phytoplankton at the sea ice margin forms the base of the food chain. Cracks in the ice provide spaces for marine mammals and birds to surface to breathe, and ice provides a platform for animals to rest, hunt and give birth (Smith and Barber 2007).

The Arctic Ocean is not a homogeneous environment, and certain areas are especially important to the ecosystem. Among the most important are the openings in the ice, both at recurring polynyas (patches of open water within the sea ice) and at the edge of the primary ice pack. This edge moves hundreds of miles as the ice expands and retreats with the seasons. Additional important ecological areas are likely to be found in areas where the seafloor community is especially diverse or productive. Other important areas include the migration corridors of whales and other marine mammals, the areas under ice where some northern fish species spawn and leave their eggs to incubate over winter and hatch in the spring, as well as the sea bottom areas where some birds and marine mammals are known to feed. (AMAP 2008b)

Figure 4-4. The U.S. Arctic Ocean provides vital habitat for seabirds that migrate to other areas of Alaska *(Photo Credit: Henry Huntington).*

4.2.1 Oil Toxicity

Oil comprises thousands of chemical compounds, with varying levels of toxicity to wildlife and habitat, based on a number of factors. Generally speaking, the water-soluble fractions (WSFs) and volatile organic compounds (VOCs) of oil are the most acutely toxic components, because they are the components of oil that evaporate into the air or mix into marine waters and often cause direct harm to organisms. These components—which include benzene, naphthalene, xylene and toluene—are toxic to wildlife and to humans. As oil remains in the environment and weathers, the WSFs and VOCs are typically lost, and the remaining oil tends to have proportionately higher levels of polycyclic aromatic hydrocarbons (PAHs). These are also toxic to humans and wildlife and have the potential to linger in the environment for years (AMAP 2008b).

Impacts on wildlife from oil toxicity occur at the individual and the group level. Individual impacts include death, disease, impaired reproduction, genetic alterations, changes to endocrine or immune functions, hypothermia and a range of other biological disorders. Group-level impacts include changes to local population sizes, community structures and overall biomass (Albers 2003 in AMAP 2008b).

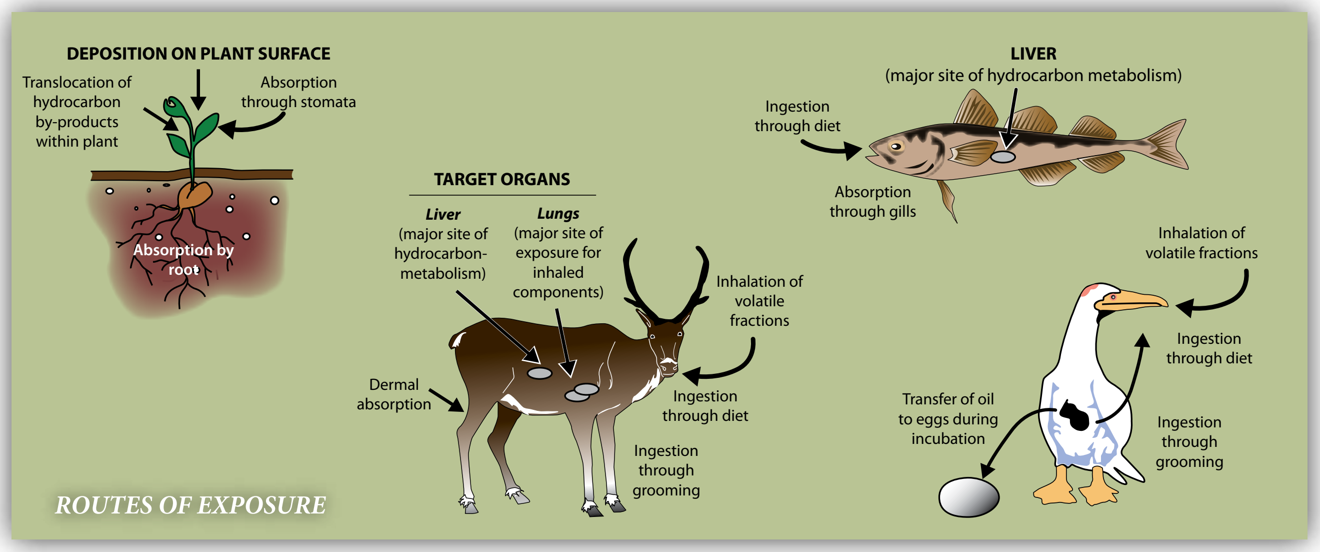
The most obvious toxic impact of spilled oil is direct contact with wildlife and habitat. Images of oiled animals and shorelines dominate typical media coverage of major oil spills. Yet toxic impacts from spilled oil persist beyond direct oiling, and the long-term toxicities and complex interactions between spilled oil and ecological processes are still the subject of considerable research and debate (AMAP 2008b, Buffagni *et al.* 2010). Although oiled wildlife provides the most vivid images of a spill's impact (Figure 4-5), the level of ecosystem harm is much greater than the acute mortality would suggest. Long-term ecosystem impacts come from chronic exposure to oil in sediments and beaches, reduced fitness of animals exposed to sublethal doses of oil, and impacts through the food web (AMAP 2008b).

Figure 4-5. The Impact of Oil on Wildlife *(Photo credits: below: Exxon Valdez Oil Spill Trustee Council; right: Paul Flint/USFWS)*—Direct oiling is only one way that spilled oil may harm animals; other less-visible impacts include loss of fertility, interruption to feeding activity, and metabolic disorder.

Plants and animals are exposed to oil toxicity through a number of pathways. Typically, mammals are exposed primarily through ingestion of contaminated food and water, inhalation of VOCs, or dermal absorption of hydrocarbons through the skin or fur. In mammals, oil is metabolized in the liver, reducing the overall concentration of PAHs and other toxic compounds to much lower levels in the organs and tissues. The by-products of hydrocarbon metabolism may also have toxic effects in mammals. Oil toxicity exposure pathways and metabolism in birds are similar to those in mammals, with the additional exposure pathway of transferring oil through the surface of incubating eggs. Fish and aquatic species can be exposed to waterborne hydrocarbons through the gills, through ingestion or by physical contact. Plant species (both terrestrial and marine) can be exposed

through direct contact (deposition) on the plant structure or absorption through the stomata or roots (Albers 2003 in AMAP 2008b). Figure 4-6 depicts typical exposure pathways for mammals, fish, birds and plants.

Figure 4-6. Exposure Pathways to Oil Toxicity *(AMAP 2008b).*



4.2.2 Persistence of Oil Spilled in the Arctic

The persistence of oil is particularly problematic in cold environments, where biological degradation is greatly slowed. In an experimental oil spill on Baffin Island in Arctic Canada, the biological degradation was determined to be negligible after two years (Humphrey *et al.* 1987). Twenty years later, although most of the original hydrocarbons had degraded, some samples had not degraded, and they contained toxic oil similar in composition to freshly spilled oil (Prince *et al.* 2002). Metabolic rates of bacteria are slowed in cold waters, and oil-degrading bacteria are relatively rare in the Arctic (AMAP 2008b). A study of bacterial oil degradation showed a latitudinal gradient, with water from Barrow, Alaska, showing slower degradation than water from Valdez, Alaska, and water from the Fletcher T3 ice island (a floating island in the Arctic Ocean north of Barrow) showing the slowest degradation of all (Arhelger *et al.* 1977 in AMAP 2008b). Bacteria from sediments in the Beaufort and Chukchi Seas were also shown to be very limited in their ability to metabolize hydrocarbons (Braddock *et al.* 2004 in AMAP 2008b).

Life phase is also a consideration in evaluating the potential toxicity of spilled oil; the larval or young stages of many organisms are particularly sensitive to oil, and the impact of exposure may not be obvious until years later and will affect future generations (Peterson *et al.* 2003). One lesson from the Exxon Valdez spill was that fish embryos and larvae are far more sensitive to oil than are adult fish, making previous toxicity calculations a drastic underestimate. Chronic exposure to weathered oil was toxic to young pink salmon and herring at concentrations 1,000 times lower than the level required to have acute effects on adult fish, showing substantial impacts at concentrations as low as 1 part per billion (Peterson *et al.* 2003). Some of the effects did not show up until much later in the life of these fish. Hydrocarbons are rapidly taken up from the water by filter-feeding invertebrates such as clams and mussels (Majewski and Scherer 1985 in AMAP 2008b) and are consumed with contaminated sediments by bottom-feeding invertebrates. The contaminants are known to bioaccumulate in their organs. Invertebrates metabolize hydrocarbons more slowly than do vertebrates, and in areas with contaminated sediments, they can be continually re-exposed (AMAP 2008b). After the Exxon Valdez spill, clams and other invertebrates living in subtidal and intertidal areas with contaminated sediments remained contaminated for more than a decade, affecting animals that fed on them (Peterson *et al.* 2003). Studies in Prince William Sound from 1999 to 2003 showed that some species, including harlequin ducks and sea otters, were still ingesting toxic oil compounds from their food sources and had not recovered as expected (Peterson *et al.* 2003).

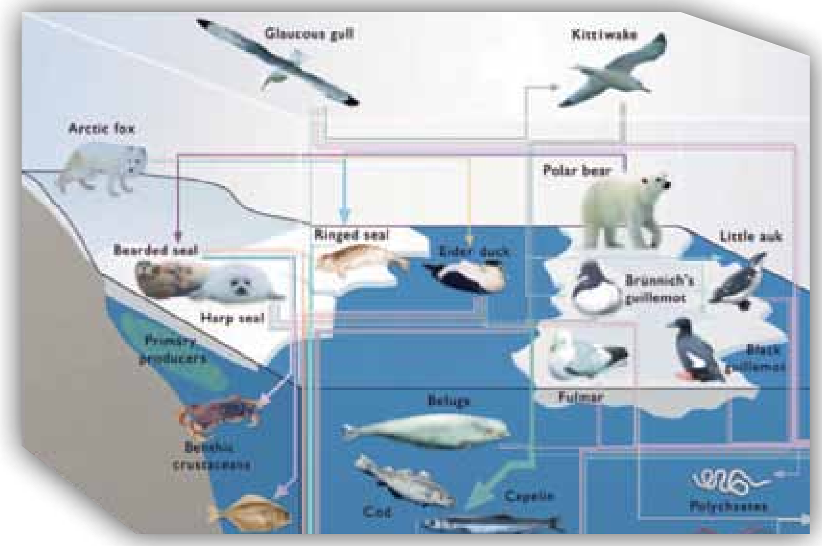
Exposure to sunlight can greatly increase the toxicity of PAHs, complicating the determination of risk levels. Photo-enhanced toxicity can occur when PAHs are exposed to sunlight before organisms encounter them, when exposure is simultaneous or when small translucent organisms (such as larvae, eggs or plankton) are exposed to PAHs and then to sunlight. For some compounds, the toxicity can be increased up to 400 times (Landrum *et al.* 1987 in AMAP 2008b). Arctic species have not been specifically studied, but the increased toxicity has been shown for sub-Arctic species of copepods and herring (Barron *et al.* 2003). This effect could have a significant impact in the Chukchi or Beaufort Sea if organisms were exposed to an oil spill during the near-constant daylight of the summer open-water season, either from a spill at that time or from a spill under or into ice that melted out in the spring.

4.3 Impact of Oil Spills on the Arctic Environment, Ecology and People

Oil can persist in the Arctic environment for decades, continuing to have toxic effects long after the initial spill. Most of the published data on oil spill impacts are based on research from past spills in Arctic and other cold-water regions. Based on this relatively small data set, we have a limited understanding of the actual and potential negative effects of spilled oil on the natural environment and the human populations that depend upon this environment (AMAP 2008b).

Characteristics of many Arctic species put them at a heightened risk for impacts from oil spills. Many Arctic animals have long life spans and slow reproductive rates, potentially prolonging population level impacts. Some animals that are high on the food chain already experience the effects of bioaccumulation of persistent organic pollutants. As a predator consumes its prey, the toxins in the body of the lower-level organism are incorporated into the predator's body in what is known as bio-magnification. This continues in each predator-prey interaction, and animals at the top of the food chain (or food web, as shown in Figure 4-7), such as polar bears and humans, can accumulate high levels of these toxins (AMAP 2002).

Figure 4-7. Typical Arctic Marine Food Web *(Source: Arctic Climate Impact Assessment 2004).*



The behavior of Arctic animals can influence their vulnerability to the effects of oil. Arctic species often aggregate in large numbers and are sometimes confined to open-water leads where oil may concentrate, increasing the chances that a spill will affect a large number of individual animals. Several species that spend all or part of the year in the U.S. Arctic Ocean are already protected under the Endangered Species Act and are facing ongoing and increasing stresses because of global climate change (Table 4-2 and Figure 4-8). All marine mammals also are protected under the Marine Mammal Protection Act.

One of the principal challenges confronting Arctic managers and decision-makers is the lack of integrated and comprehensive information about the composition, structure and functioning of Arctic marine ecosystems (e.g., Richter-Menge *et al.* 2008, North Pacific Fishery Management Council [NPFMC] 2009). Even basic information, such as knowledge of the species that inhabit the U.S. Arctic Ocean permanently or seasonally, is substantially incomplete, resulting in an incomplete understanding of marine ecosystem structure and functioning. Without adequate scientific information about the Arctic marine species, we do not have the ability to determine whether impacts of oil spills on marine species will be significant (MMS 2007a).

The North Pacific Fishery Management Council has set an example of how to sustainably manage natural resources in the Arctic by taking a science-based and precautionary approach toward fishery management (NPFMC 2009). The council adopted a fishery management plan that prohibits commercial fishing unless new information demonstrates that it can be conducted sustainably, without harming the ecosystems or peoples of the Chukchi and Beaufort Seas. The council acknowledged that current scientific information is insufficient to accurately predict the impact of commercial fishing on ecosystems and subsistence activities in the Arctic and decided to take a proactive and precautionary approach.

Table 4-2. Threatened and Endangered Species Found in the U.S. Beaufort and Chukchi Seas *(Source: U.S. Fish and Wildlife Service 2010a).*

Common Name (Species Name)	Threatened or Endangered	Location Within U.S. Arctic Ocean (Beaufort and Chukchi Seas)
Bowhead whale *(Balaena mysticetus)*	Endangered	Beaufort and Chukchi Seas
Fin whale *(Balaenoptera physalus)*	Endangered	Chukchi Sea (occasional)
Polar bear *(Ursus maritimus)*	Threatened	On sea ice and coastlines of Chukchi and Beaufort Seas
Spectacled eider *(Somateria fischeri)*	Threatened	Chukchi Sea
Bearded seal *(Erignathus barbatus)*	Candidate for listing	Beaufort and Chukchi Seas
Ringed seal *(Phoca hispida)*	Candidate for listing	Beaufort and Chukchi Seas
Pacific walrus *(Odobenus rosmarus divergens)*	Candidate for listing	Chukchi Sea

Figure 4-8. Polar Bear on Ice *(Photo Credit: Canadian Coast Guard)*—The polar bear was recently declared a threatened species under the Endangered Species Act. Changes to polar ice coverage are putting pressures on polar bear populations. A major oil spill in the U.S. Arctic Ocean could harm or kill polar bears that are exposed to spilled oil.

4.3.1 Lower Trophic Level Species

Lower trophic level species refer to those at the bottom of the typical food web. An experimental exposure of Arctic phytoplankton to oil caused significant and differential mortality, with some types of phytoplankton, such as diatoms, proving far more sensitive than others (AMAP 2008b, citing Hsiao 1978). Even if plankton numbers recovered, a large oil spill could cause a substantial shift in species composition at the bottom of the food chain that would have reverberating impacts across the food web.

Benthic invertebrates are important food sources for Arctic species such as the walrus and gray whale. Amphipods (Figure 4-9), which are bottom-dwelling invertebrates that scavenge detritus (dead food particles) on the seafloor, are particularly sensitive to certain toxic components of oil (NRC 1985 in AMAP 2008b). Amphipods grow more slowly in the Arctic, and populations that are negatively affected by a spill may be slow to recover and may also cause a shift in the food web. For example, during the first five years after the 1996 Sea Empress spill in the United Kingdom, amphipod populations virtually disappeared and were replaced by polychaetes, a type of marine worm (Edwards and White 1999 in AMAP 2008b). Ten years after the 1978 Amoco Cadiz spill off the coast of France, populations of amphipods had recovered to only 39 percent of pre-spill levels (Dauvin 1989 in Highsmith and Coyle 1992).

Although there are limited data on recolonization of seafloor areas affected by oil contamination, other natural processes, such as ice scours, have been shown to disrupt Arctic bottom-dwelling communities. A study on recolonization of bottom-dwelling organisms after ice scours showed that recolonization is a slow process in the Arctic, and only about 65 percent of the organisms disrupted by an ice scour had returned nine years after the disturbance (Conlan *et al.* 1998). Large mollusks (snails and mussels) are typically among the last organisms to recolonize disturbed areas.

Figure 4-9. Lower Trophic Level Species *(Photo Credit: NOAA)*— Lower trophic level organisms, such as amphipods (left) and diatoms (right, with amphipod), provide a link between lower- and upper-level trophic organisms within the short, efficient Arctic food web.

4.3.2 Fish

Larvae, eggs and young are generally more sensitive to PAHs than are adult fish (Peterson *et al.* 2003). In the U.S. Arctic Ocean, the life histories of pink salmon and capelin put these two fish species at an elevated risk of being affected by oil spill toxins. Salmon and capelin spawn during the open-water season (when drilling activity would be likely to take place) in large concentrations in nearshore areas (MMS 2008). Capelin are highly specific with regard to their spawning habitat, and salmon generally return to their birth streams, putting both at risk if their spawning habitat were exposed to an oil spill (MMS 2008).

As seen in the aftermath of the Exxon Valdez spill, contamination of nearshore spawning habitats can persist for many years, affecting multiple generations of young fish. Pacific herring populations in Prince William Sound suffered a dramatic decline after the 1989 spill, which occurred a few weeks before the spawning season. It is estimated that 40 to 50 percent of the egg biomass was exposed to oil from the spill, as was a significant proportion of the adult herring. Lesions and elevated hydrocarbon levels were documented in some adult Pacific herring from the oiled areas. Laboratory studies showed abnormalities and possible depressed immune functions in Pacific herring exposed to oil. Four years after the spill, there was a major collapse of the herring fishery, which has yet to recover to pre-spill levels (Brown and Carls 1998).

Arctic cod is a key species in Arctic food webs. This abundant fish is the primary connection between plankton and larger animals, and impacts on them would be likely to affect many of their predators, such as the ringed seal. Arctic cod spawn under sea ice in winter, and the eggs hatch during the plankton bloom that occurs with spring breakup of the sea ice (AMAP 2008b). They would be vulnerable to an under-ice spill during the spawning period, or to a spill that concentrated in the lead system during breakup.

4.3.3 Marine Mammals

Impacts on marine mammals could include the ingestion of oil and the inhalation of vapor from crude oil, loss of insulation by oiling, and effects from contaminated prey (NRC 2003b). Inhalation of volatile compounds from fresh crude oil is known to damage the respiratory system, nervous system and liver of marine animals surfacing to breathe (AMAP 2008b, NRC 2003b). However, there are few data supporting a link with mortality (NRC 2003b). An estimated 302 harbor seals were killed in the Exxon Valdez spill, probably from inhalation of toxic fumes (Frost and Lowry 1994). PAHs from weathered oil are toxic to developing fetuses in at least some mammals and probably have other health consequences. However, the long-term health impact of sublethal oil exposure on marine mammals is generally not known.

Some marine mammals are dependent on fur for insulation, and oiling of their fur causes substantial acute mortality. Direct oiling of fur killed 1,000 to 2,800 sea otters in the Exxon Valdez spill (Peterson *et al*. 2003). In the Arctic, this could affect ice seal pups, polar bears and Arctic foxes. A 1969 spill off the coast of Canada during harp seal breeding season oiled 10,000 to 15,000 seals, causing significant mortality to the pups (AMAP 2008b). Polar bears and Arctic foxes, both present in the Beaufort and Chukchi Sea regions, would also be vulnerable to oil ingestion from grooming their fur.

Predatory mammals such as toothed whales (e.g., beluga whales), seals and polar bears are vulnerable to bio-magnification of contaminants from their food sources (Figure 4-10). Even when marine mammals have the potential to escape the oil spill, they may not do so. Although some whale species, such as the filter-feeding bowhead whales, have been observed to avoid oil-contaminated areas, other species have shown no avoidance behavior. After the Exxon Valdez spill, killer whales were observed swimming through slicks with no obvious attempts to avoid them (Matkin *et al.* 2008). After this exposure, high mortality rates (20 to 40 percent) were observed in subsequent years in both a resident and transient pod of killer whales in Prince William Sound (Peterson *et al.* 2003). Because the effects from an oil spill for long-lived species such as toothed whales are not immediately detectable, assessing the impact of a spill may be difficult without adequate information about populations, such as trends, population size and reproductive rate (NRC 2003b).

Endangered bowhead whales are vulnerable to oil spill impacts because of their concentration at ice edges and leads where spilled oil may concentrate (Engelhardt 1987 in MMS 2008). During spring migration (Figure 4-11), the entire population of bowhead whales in the Bering, Chukchi and Beaufort Seas (BCB population) travels north through the U.S. Arctic Ocean ice lead and polynya system, and their path is relatively constrained (AMAP 2008b). This migration path is also the primary calving area for this population of whales.

A spill into ice leads or polynyas in the spring could have potentially devastating effects, trapping the whales where they may encounter fresh crude oil. Calves would be even more vulnerable than adults, because they need to surface more often to breathe and have less ability to travel under ice or to break ice to breathe. Filter-feeding bowhead whales are also sometimes observed aggregating in large numbers during the summer open-water season, when they could also be vulnerable to a spill. Like the bowheads, beluga whales use the spring lead system to migrate and would be exposed to a spill that concentrates in these leads.

Figure 4-10. Whales in Ice—Beluga whales (left) are an important Arctic species that feed higher in the food web and may be exposed to toxic compounds that are accumulated in lower trophic species. Bowhead whales (below) are an endangered species. *(Photo Credits: USFWS/Brad Benter)*.

Pacific walrus distribution varies seasonally and is limited by water depth and ice conditions. Walruses have historically followed the receding sea ice, from which they have easy access to feeding grounds in shallow water on the continental shelf ([U.S. Fish and Wildlife Service 2010], Jay and Fishback 2008, Burns *et al.* 1980, Fay *et al.* 1984, Fay 1982, Fay 1985). Most of the population spends the summer months in the pack ice of the Chukchi Sea while the (predominantly) male portion of the population hauls out onto land in the Bering Sea (Fay 1981). Walruses are considered an ice-associated species because they use floating sea ice for giving birth, nursing calves and resting and as passive transport to feeding areas (See Figure 4-12). In the Chukchi Sea, they also concentrate at coastal haul-outs, particularly when the ice edge has shrunk away from their feeding grounds on the continental shelf. This is becoming more frequent as global climate change leads to a shrinking of the summer ice cover ([USFWS 2010b], Jay and Fishback 2008, U.S. Geological Survey 2010, Hassol 2004).

Although Pacific walrus are not listed as threatened or endangered under the Endangered Species Act, several petitions have been made to the U.S. Fish and Wildlife Service to officially list this species (USFWS 2009). An oil spill that contacts an aggregation of walruses or displaces them from this important habitat may have a severe impact on the population, exacerbated by their low natural rate of reproduction. They would also be sensitive to impacts on their food supply. Information is scarce on the large mollusks that form the walrus's primary food source, but they are slow-growing and would be expected to recover slowly after an oil spill (MMS 2008). Suspension-feeding invertebrates such as mollusks metabolize hydrocarbons slowly, so walruses would be exposed to contamination by eating them. Walruses also stir up sediment when feeding and could be exposed to oil residue. Because of their long life span, walruses could suffer severe effects from this bioaccumulation of oil-derived contaminants.

4.3.4 Birds

Seabirds are very vulnerable to oil, particularly in cold environments. A square-inch spot of oil can compromise the water repellency of the feathers, potentially causing hypothermia (MMS 2008). A large spill can cause a massive acute die-off of oiled birds. Seabird deaths from the Exxon Valdez spill were estimated at 250,000 (Peterson *et al.* 2003). Many Arctic bird species have characteristics that make them especially vulnerable to oil spills. These birds make long-range migrations, aggregate in colonies and have low reproductive rates and long life spans (Figure 4-13). Birds nesting in dense colonies are especially vulnerable to spills affecting their breeding sites. Many seabirds congregate to feed at ice edges, polynyas and open leads, where their prey species congregate and where oil may concentrate (AMAP 2008b).

A number of studies have shown that seabird colonies can be wiped out by oil spills. A puffin colony crashed after the Amoco Cadiz spill in 1978 (Clark 1984 in AMAP 2008b), and a guillemot colony in Southern California was wiped out because of a number of oil spills in the 1980s (Parker *et al.* 2007 in AMAP 2008b). Oil spills from sinking ships were probably responsible for the disappearance of puffins and guillemots from the English Channel during World War II (Gaston and Jones 1998 in AMAP 2008b).

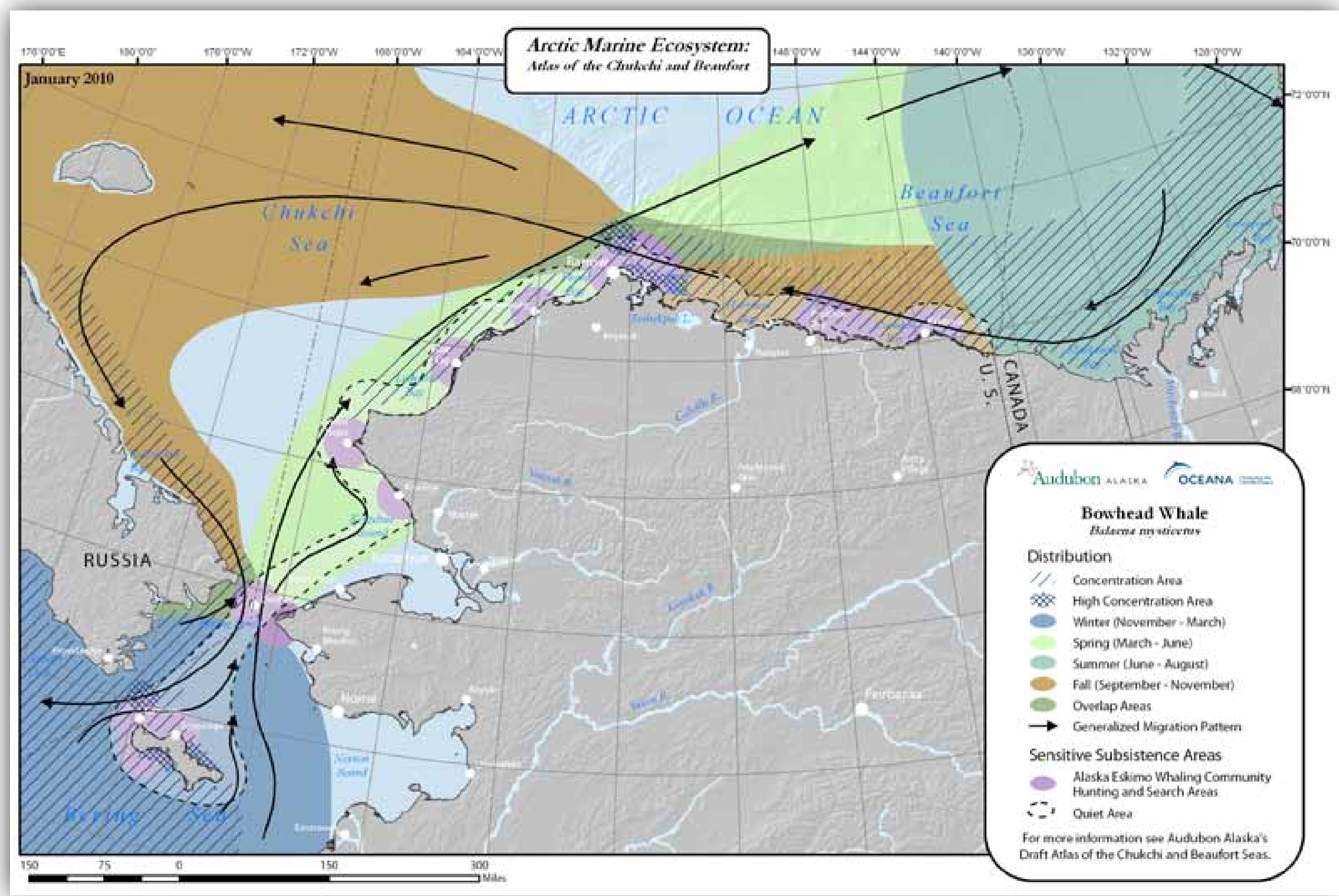


Figure 4-11. Bowhead Whale Migration Routes and Concentrations.

Figure 4-12. Herd of Pacific Walrus Hauled Out on Sea Ice *(Photo Credits: left, USFWS/Brad Benter; right, U.S. Geological Survey/Sarah Sonsthagen)*

Figure 4-13. Arctic Seabirds *(Photo Credits: left, Ground Truth Trekking; right, Mike Dunn/NOAA)*—Ivory gulls (lower right) concentrate at the ice edge and polynyas to feed. Northern fulmar (upper right) live as long as 30 to 40 years and produce one egg per year, starting between the ages of 6 and 12. Seabird colonies along the Arctic shoreline often provide nesting habitat for multiple species, such as this colony on Cape Lisburne, left.

4.3.5 People

A large oil spill could significantly affect the people and communities along the Chukchi and Beaufort Sea coasts. The most significant impact to the approximately 8,000 people living in this region would be on the subsistence resources that provide much of their diet and form the basis for their culture and social well-being. In the short term, both the spilled oil and the response activities could lead to disturbance or displacement of species important to subsistence fishers and hunters. Concerns over tainting or contamination of subsistence foods could lead to avoidance, both in the short term and into the future. If the oil spill caused significant population-level impacts to these species, their availability to hunters would be affected for a long time after the spill (Figure 4-14). A reduction in the availability or safety of subsistence foods could have a profound impact on the economy and culture of Arctic communities on the U.S. and Russian coastlines (AMAP 2008b and MMS 2008). Reductions in the overall caloric input from subsistence food have also been documented to have negative impacts on the physical and mental health of Arctic indigenous communities (Wernham 2007).

Bowhead whales are an important subsistence resource for native communities in the U.S. Arctic. Depending on the timing, a spill could stop the spring or fall hunt because of displacement of the whales or concerns about tainting of the meat. Also, local hunters could be pulled into spill response efforts, preventing them from hunting (MMS 2008). Even if the oil spill has no long-term impact on whale populations, bowheads are known to avoid contaminated areas, making them more difficult for hunters to access. In 1944, Barrow elder Thomas Brower Sr. observed an oil spill from a U.S. Navy vessel in the Plover Islands east of Barrow, where about 25,000 gallons spilled.

> *"In 1944, I saw the effects of an oil spill on Arctic wildlife, including the bowhead. … The first year ... I observed how seals and birds who swam in the water would be blinded and suffocated by contact with the oil. It took approximately four years for the oil to finally disappear. I have observed that the bowhead whale normally migrates close to these islands in the fall migration. … But I observed that for four years after that oil spill, the whales made a wide detour out to sea from these islands. … If there were a major blowout, all the Inupiat could be faced with the end of their marine hunting." (Brower, 1978)*

In addition to bowhead whales, many other subsistence resources of the Arctic Ocean are causes for concern, including birds, fish and other marine mammals. On the Arctic coast, marine mammals and fish often make up 60 percent of a community's diet (MMS 2008). An oil spill could cause these foods to be less abundant, more difficult to access or tainted by contaminants, or perceived to be tainted. Loss of these subsistence resources could have economic impacts as people are forced to buy more of their food. Such a loss could also have negative social impacts from the loss of culturally important foods and activities, as well as adverse effects on physical and mental health. Psychological impacts of oil spills have been documented in other areas, especially among indigenous peoples (AMAP 2008b).

Although the impact of oil spills on local communities is an obvious concern, the broader impact of oil and gas activities adjacent to human populations is not well understood. An Arctic Council study recommends additional research into these potentially negative impacts, noting:

> *"In general, there is no good characterization of contamination sites in the Arctic region and a complete lack of exposure information for Arctic populations living near to oil and gas activities." (AMAP 2008b)*

Public health is not generally included in the National Environmental Policy Act, from which the environmental impact statement (EIS) process evolved in the United States. In a congressionally commissioned review of the impacts of oil and gas development in Alaska's Arctic, the National Academy of Sciences concluded that the effect on human health was an area in great need of additional study and attention in the planning process (NRC 2003b). Despite the recommendations in that report, the impact on the local population is still strikingly underemphasized in the planning process. Few NEPA documents contain any explicit analysis of baseline public health conditions in the region, nor do they assess the potential direct, indirect and cumulative impacts on the human population (Wernham 2007). This lack of attention to the people who live, work and subsist in the region means that decisions are made without a full and fair consideration of local populations, that the local population may be exposed to potentially preventable risks and harm, and that the benefits of well-planned development go unrealized. This is of particular concern because the baseline prevalence of some health problems that can be affected by oil and gas activities are markedly elevated in the North Slope region compared with the general U.S. population. Health information should be used in the NEPA process to help influence decisions about development.

Figure 4-14. Marine mammals are important in Inupiat culture and as subsistence food items. *Clockwise from right: bowhead whale bones, Barrow, Alaska (Photo credit: Raychelle Daniel); drums (Photo credit: Henry Huntington); bowhead whale muktuk (Photo credit: Henry Huntington).*

5 LIMITATIONS OF EXISTING OIL SPILL RESPONSE TECHNOLOGIES IN THE U.S. ARCTIC OCEAN

Oil spill response is a labor- and resource-intensive activity that typically results in the removal of only a small fraction of the released oil. The Arctic marine environment poses unique challenges to oil spill response technologies and tactics that may reduce the efficiency of response equipment or, in some cases, prevent response operations entirely because of technological limits, logistical challenges and safety concerns.

As the Deepwater Horizon spill illustrated, it is a major challenge to control a well blowout while simultaneously attempting to clean up the oil. Of the 4.9 million barrels spilled during the three-month Deepwater Horizon incident, an estimated 25 percent was recovered through skimming, burning or direct recovery. Most of the oil recovery—17 percent of the total spill—occurred at the wellhead. On-water skimming operations removed only 3 percent of the total spill amount, or 147,000 of the 4.9 million barrels spilled. In-situ burning treated 5 percent of the oil (245,000 barrels), and chemical dispersants treated 8 percent, or 392,000 barrels (Lubchenco *et al.* 2010). At the height of the response, more than 6,500 response vessels worked on that spill, with more than 3 million feet of containment booms and nearly 900 skimmers (Joint Information Center 2010). Yet 75 percent of the oil (3.67 million barrels) was left in the Gulf of Mexico to evaporate or dissolve naturally, chemically disperse, or remain in the environment as residual oil (Lubchenco *et al.* 2010).

The response estimates from the Deepwater Horizon spill are relevant to the discussion of oil spills in the Arctic Ocean because they demonstrate that existing oil spill response technologies cannot remove all the oil spilled in the marine environment. The Deepwater Horizon spill occurred in temperate waters during the spring and summer. The Gulf of Mexico coastline has significant infrastructure in place to support a major response, and every available resource was enlisted, yet 75 percent of the oil could not be treated or recovered. In the Arctic Ocean, where sea ice, fog, wind, rough seas, darkness and lack of infrastructure make spill cleanup even more difficult and probably less effective, how much of the oil spilled during a well blowout would escape containment and cleanup?

Experts agree that oil spill response systems do not function as effectively in Arctic waters, but opinions vary as to how those limits affect the overall capacity to respond to oil spills in the Arctic Ocean (Fingas 2001). Even if the U.S. Arctic had equipment stockpiles equivalent to those used during the Deepwater Horizon response, would that arsenal of equipment make a difference in terms of reducing the environmental consequences of a well blowout in the U.S. Arctic?

(Photo credit: Skimmer deployed in icy water, *BOEMRE*)

This chapter reviews the major technologies in use for stopping a well blowout and cleaning up an oil spill and examines how each may be limited in the Arctic Ocean environment.

5.1 Arctic Ocean Challenges

Arctic conditions—sea ice, low visibility, high winds, rough seas and cold temperatures (discussed in Section 2.1)—would complicate all aspects of a spill response, from stopping a well blowout to predicting or tracking the movement of an oil spill trapped in sea ice (Table 5-1). All of the major spill cleanup technologies face operating limits that are tied to wind speed, wave height, ice conditions and visibility (Potter 2004). Once the limit is reached for any one or combination of these factors, spill response operations may be slowed or shut down for days, weeks or months.

Table 5-1. Typical Arctic Conditions and Potential Impacts on Spill Response Options (Adapted from Nuka Research 2007b).

ARCTIC	POTENTIAL IMPACTS TO SPILL RESPONSE			
CONDITIONS	All Response Options	Mechanical Recovery	In-Situ Burning	Dispersants
Sea Ice [1]	**Challenges:** Difficult for vessels to access spill site. Difficult to sense, track or model movement of oil in, on or under sea ice. Ice-class vessels required in higher ice concentrations. Slush ice can clog water intakes. Ice scouts may be needed. Ice-management vessels may be needed in addition to primary response vessels. Experienced vessel operators must be familiar with ice. Ice conditions may change suddenly and create dangerous conditions. **Benefits:** Oil may weather and spread more slowly.	**Challenges:** Ice may tear, lift or move containment boom. Reduced encounter rates for skimmers. Ice may clog skimmers or reduce efficiency. Ice may clog pumps or cause them to fail. Deflection of ice away from skimmers may inadvertently deflect oil. Limited maneuverability may prevent or delay accurate skimmer or boom deployment. Attempts to deflect the ice from recovery areas may also deflect the oil. Ice must be separated from recovered oil. **Benefits:** Ice may contain oil in pools for small-batch recovery.	**Challenges:** Certain ice conditions (i.e. slush ice) may reduce burn effectiveness or impede ignition. Difficult to deploy fire boom. Difficult to track and recover burn residue. Impact of smoke plume and soot to ice unknown. **Benefits:** Ice may provide containment for burning.	**Challenges:** Cannot access oil under ice. Ice reduces mixing energy. Dispersants generally less effective at lower salinities. In most regions, dispersants are not considered an operational technology for use in sea ice. Little information about dispersant toxicity to Arctic organisms. **Benefits:** None apparent.

1 Sea ice is a prominent feature of the Arctic marine environment. The generic term "sea ice" encompasses a wide range of ice conditions. Sea ice may be present year-round, or it may follow an annual freeze-melt cycle. Ice conditions may be described in terms of the formation of the ice or the percent coverage. The World Meteorological Organization ice classification system and terminology are used in this report (WMO 2005).

ARCTIC CONDITIONS	POTENTIAL IMPACTS TO SPILL RESPONSE			
	All Response Options	**Mechanical Recovery**	**In-Situ Burning**	**Dispersants**
High Winds	**Challenges:** Unsafe to operate vessels and deploy on-water equipment during high winds. Aircraft cannot fly above certain wind thresholds. High winds drive sea state, may enhance wave height or create choppy seas. High winds may combine with low temperatures to create dangerous wind chill. **Benefits:** Strong directional winds may drive oil away from sensitive areas.	**Challenges:** High winds can move boom or tear it from anchor. Difficult to keep vessels and equipment on station. **Benefits:** None apparent. Increasing winds make all aspects of on-water recovery more challenging and eventually create safety issues.	**Challenges:** Difficult to ignite oil in high winds. Aircraft cannot deploy heli-torches in high wind. High winds may drive plume. **Benefits:** None apparent. In-situ burning is not generally safe or feasible in high winds.	**Challenges:** Difficult to accurately spray dispersants. Aerial spraying not safe during high winds. Cannot conduct application monitoring from aircraft. **Benefits:** Wind-driven sea state will provide mixing energy for dispersants and oil if the dispersants can be safely applied.
Cold Temperature	**Challenges:** Potential for hypothermia among responders. More frequent breaks (every 10 to 15 minutes in some cases) needed to warm up. Unsafe to work at extreme low temperatures. Cold may cause brittle failure in some metals. Cold air may freeze sea spray, creating slick surfaces. Icing conditions may make vessels unstable. Natural bio-degradation of oil slowed. **Benefits:** Oil may weather more slowly, increasing window of opportunity for response.	**Challenges:** Skimmers freeze up. Sea spray may freeze on boom, causing it to fail. Pumps may freeze up. Increased oil viscosity makes oil difficult to recover and pump. **Benefits:** None apparent. Cold temperatures will slow or limit nearly all aspects of spill response.	**Challenges:** Ignition more difficult. Oil may burn more slowly or less completely. **Benefits:** No specific benefits.	**Challenges:** Increased oil viscosity may reduce dispersant effectiveness. Some studies have shown reduced efficiency in cold waters. **Benefits:** None apparent.
Limited visibility (including darkness)	**Challenges:** Limit or preclude safe vessel operations. Aerial operations typically not conducted during darkness, heavy fog or low ceiling. Difficult to see, track or locate oil spill.	**Challenges:** Cannot conduct mechanical recovery in darkness or low visibility unless work lights can be used. **Benefits:** No apparent benefits.	**Challenges:** Cannot conduct in-situ burning during darkness. Fog or low visibility may limit aerial operations. **Benefits::** No apparent benefits.	**Challenges:** Darkness or low visibility that limits aerial operations will preclude aerial application and observation. Vessel application requires visual confirmation of slick location. **Benefits:** No apparent benefits.
Sea state (high waves, strong tides)	**Challenges:** High waves limit small boat operations. Strong currents challenge vessel operations. **Benefits:** Calmer, low current sea states are typically more favorable than high sea state.	**Challenges:** Booms and skimmers do not function well at high sea states. Short, choppy waves may be more limiting than longer period waves. Moderate to high currents cause boom to fail. **Benefits:** None apparent. Increases in wave height and period and moderate to high currents all make mechanical recovery more difficult.	**Challenges:** High sea states make containment and ignition difficult and potentially unsafe. **Benefits:** None apparent. Increases in wave height and period and moderate to high currents all make in-situ burning more difficult.	**Challenges:** Vessel-based application limited by sea state based on vessel size. **Benefits:** Sea state should not inhibit aerial application (assuming no high winds). High sea states typically enhance the effectiveness of chemical dispersants.

Other characteristics of the Arctic Ocean and the Arctic region—lack of infrastructure, limited transportation options, and distance from major ports (Section 2.2)—also affect the ability to meet the basic requirements for implementing a major oil spill response.

Oil spill response equipment and systems face many limits, including the overall efficiency of the technique or equipment. Efficiency is a measurement or estimate of how well the equipment or technique might function under ideal conditions to clean up or treat spilled oil. No oil spill cleanup technique is 100 percent efficient, and even spill cleanup measures that are shown to have very high efficiencies under test conditions face significant limits in real-world situations.

There are several basic requirements for on-water oil spill cleanup operations that also apply in the Arctic, and failure to meet any of these requirements can reduce the response efficiency significantly or halt operations altogether.

- Spill managers must be able to locate and track the movement of the oil spill.
- Response equipment and trained responders must be transported to the spill site.
- Available response equipment must be able to access the spilled oil.
- The response equipment and technologies must be appropriate for the type of oil spilled and the conditions under which the equipment is used.
- Sufficient storage devices and disposal plans must be in place to deal with oil, oily liquid and other contaminated materials recovered during the response.
- Communications networks must be in place so that responders can communicate among themselves and with response managers in the incident command post. Ground-to-air, vessel-to-air, vessel-to-vessel and ground-to-vessel communication networks must be in place.
- Vessels or aircraft that provide the basis for response operations must be able to safely operate in the weather and environmental conditions.
- Food, water and housing must be provided for response personnel.
- All operations must meet basic safety parameters to prevent injury to responders.

5.2 Stopping a Subsea Well Blowout

There are a number of well control measures that can be taken to mitigate the intrusion of oil and gas into the well bore, if those measures fail for any reason an open orifice blowout can occur. In this case, the first and most important task in any oil spill is stopping the flow of oil into the environment. In the case of a blowout, the uncontrolled flow from the well must be stopped. Subsea blowouts are especially difficult to stop because the blowout preventer and wellhead are located underwater. Controlling a subsea well blowout may require months, as was the case with the Deepwater Horizon spill.

The options for controlling a subsea well blowout are limited and time-consuming. The two options most often discussed for use in subsea well blowouts are subsea well control or containment measures (sometimes described as capping) and drilling of a relief well (Grace 2003).

5.2.1 Subsea Well Containment and Control

Once the well has bypassed the blowout prevention (BOP) system and achieved an uncontrolled blowout state, the wellhead control equipment may suffer considerable damage. In this case, one option to reestablish control of the well would be to install some kind of containment barrier. It is difficult to install a containment barrier to control a subsea well blowout because of the difficulty of accessing the underwater wellhead. The Deepwater Horizon blowout provided the opportunity for responders to test and refine several different approaches to subsea well containment and control, and resulted in some novel approaches that have the potential to substantially improve existing technologies in this area (Joint Industry Subsea Well Containment and Control Task Force 2010).

Before the Deepwater Horizon well blowout, no prefabricated subsea well containment devices were available for immediate use. Several devices were constructed after the Deepwater Horizon blowout, and ultimately one of those devices was successful in sealing in the oil. A joint industry task force is working on a long-term plan to develop tools and equipment to establish a standing capability to use prefabricated structures or equipment to quickly control subsea well blowouts. Areas of new research include well containment devices for use on the seafloor (Figure 5-1), equipment and technologies for use within the subsea well, and devices for subsea collection and processing of oil recovered from the blowout plume (Joint Industry Subsea Well Containment and Control Task Force 2010).

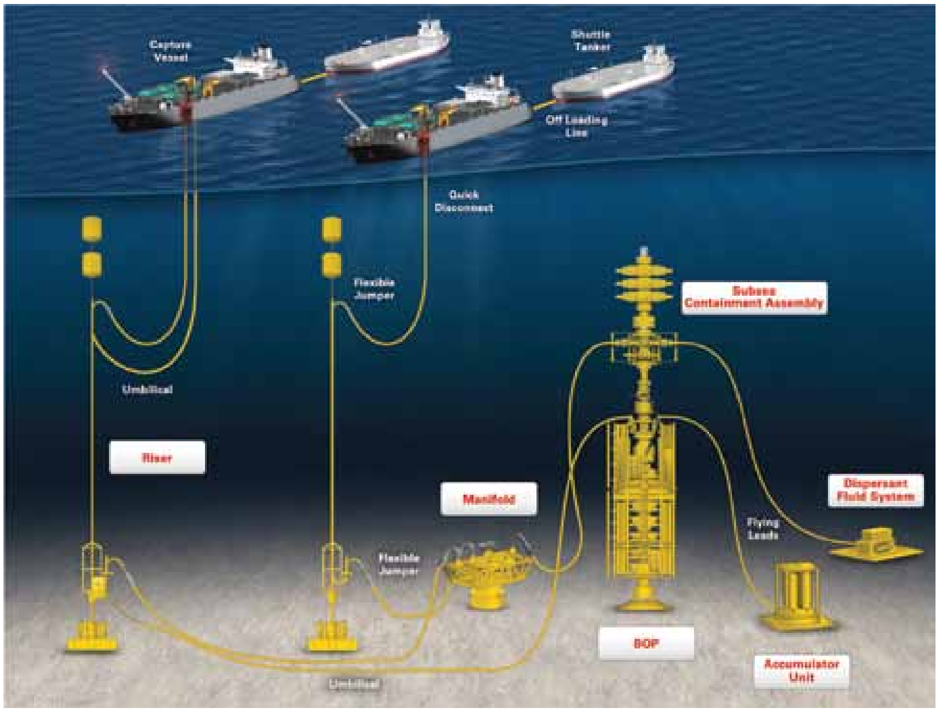


Figure 5-1. Subsea Well Containment System Proposed for Use in Gulf of Mexico—During the Deepwater Horizon well blowout, a subsea containment system was proposed to stop the uncontrolled flow from the well. Research is ongoing into other potential subsea well control structures; however, at present there have been no technologies proposed or developed to control subsea well blowouts in the Arctic.

The transfer of technologies from the Deepwater Horizon blowout and the ongoing work of the Subsea Well Control and Containment (SWCC) Task Force are likely to improve the techniques available for subsea well blowout control. An action plan for the SWCC Task Force is scheduled for completion Dec. 31, 2010. Preliminary documents from the task force do not indicate whether the research and development activities will include an Arctic component.

The introduction of new techniques and technologies for subsea well containment and control is likely to improve future options for reducing the amount of oil released during a subsea blowout. If operators are able to develop and demonstrate the ability to quickly and effectively contain subsea wells, the risks would be significantly reduced. However, like all engineered systems, subsea well containment and control measures would require certain adaptations or enhancement for use in the Arctic Ocean. Equipment installed on the seafloor in shallow water would risk damage or destruction from ice scouring if left in place over the winter. The specialized equipment and trained personnel required to install subsea well control or containment devices would need to be transported to the well site, because no subsea well containment equipment or personnel are located in Alaska nor has anything been fabricated and demonstrated to withstand Arctic conditions.

5.2.2 Relief Wells

A relief well intercepts the subsurface well bore of the out-of-control well (Figure 5-2). Drilling a relief well is often not the first or only well control option selected because of the time it takes to move a rig into the area of the blowout and drill a relief well. However, a relief well is the most reliable method for stopping a blowout. If a rig is on location or nearby, it may be possible to shut down its drilling operations to aid the blowout response. If no rigs are available nearby, then substantial time will be required to move a rig into the area. In the interim, other well control operations may be initiated, as was the case in the Deepwater Horizon blowout in the gulf, where a subsea containment structure was successfully installed while relief well drilling continued to completion.

5.2.3 Challenges to Well Control in the U.S. Arctic Ocean

The ability to control a blowout in the U.S. Arctic Ocean will vary, based on the ice season and the location of the well. Even if Arctic Ocean drilling is limited to open-water season, it is possible that a blowout that occurs late in that season could continue during the freeze-up, and the blowout control and response could be affected by encroaching sea ice.

Data are sparse and poorly compiled on the international experience with Arctic subsea oil well blowout control. Some conclusions can be drawn, however, by considering the known challenges of well control technologies and relief well drilling in temperate or sub-Arctic conditions, and then factoring in Arctic conditions.

All blowout control measures require time to mobilize and deploy the required equipment, and a period of weeks or months may pass before well control is achieved. For example, it took several months to mobilize a rig and drill the relief well in a gas well blowout at the Steelhead platform in Cook Inlet, Alaska. The blowout occurred in December 1987, but the relief well was not completed until June 1988 (Petterson and Glazier 2004). In the U.S. Arctic Ocean, if a relief well cannot be completed before pack ice encroaches on a drill site, it is possible that a blowout could continue uncontrolled through the eight- to nine-month ice season. If subsea containment or control measures controlled the blowout, the containment system would have to be engineered to withstand the arctic winter. Ultimately, a relief well would probably be required to completely control an Arctic subsea well blowout, unless the well were to naturally seal itself with rock fragments from the collapsing formation.

5.3 Applying Oil Spill Cleanup Methods in the Arctic Ocean

The challenges associated with controlling a well blowout in the Arctic Ocean are only the first part of the equation. Cleaning up spilled oil in the marine environment—whether from a blowout or another spill source—is a tedious and labor-intensive process that, even under the best of circumstances, may result in the recovery or removal of only a small fraction of the total spill volume. In the Arctic, every step of that process may be more difficult or even impossible under certain conditions. Most technologies used in response to oil spills in sea ice have been adapted from those typically used on open water and land. Although on-water response technologies may transfer to open-water Arctic conditions, sea ice has been demonstrated to reduce the efficiency of many response methods and to preclude the use of others (AMAP 1998).

Oil spill response methods are generally divided into three main categories: mechanical recovery, in which oil is corralled using natural or man-made barriers and removed using skimmers and pumps; nonmechanical recovery, in which chemicals, burning or bioremediation are used to treat an oil slick; and manual recovery, in which oil is removed with hand tools or machines. Most operations in Arctic waters rely on a combination of mechanical recovery and two types of nonmechanical treatment—in-situ burning and dispersant application—to clean up or treat spilled oil. All of these options face limits from environmental and weather conditions (Table 5-1).

All three response technologies require surveillance and spill tracking to identify the location, extent and condition of the spilled oil so that the appropriate response equipment and tactics may be selected. All three also require logistical support to transport equipment and trained personnel to the spill site, deploy and operate the equipment, and decontaminate the equipment when response operations are complete. Spill responders must be able to safely access the spill site—often one of the biggest challenges, particularly in remote areas. With all three oil spill response options, time is critical. As soon as oil is spilled in water, it begins to spread, evaporate and emulsify, and as time passes, it generally becomes more difficult to track, contain, recover and treat. The quick mobilization and deployment of response equipment and trained personnel are important to the overall response effectiveness.

5.3.1 Spill Tracking, Surveillance and Modeling

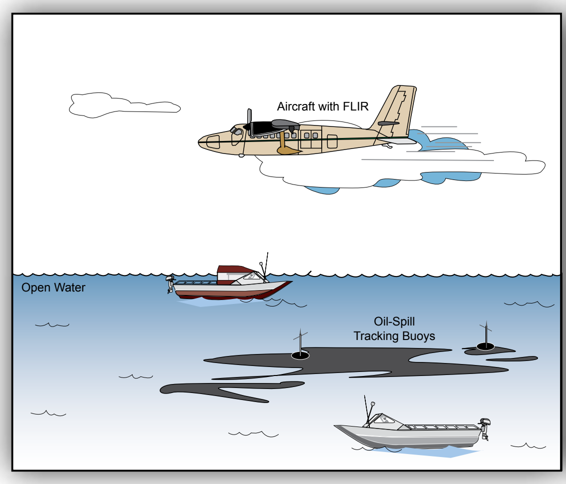
Several technologies are available to detect and track oil spills on open water and ice. These include tracking buoys, satellite imagery, aerial surveillance, visual observations, on-ice surveys, and trajectory models. All have their strengths and weaknesses, and many are limited by Arctic conditions. Figure 5-2 shows examples of these technologies (Glover and Dickins 1999, Dickins and Buist 1999, Owens *et al.* 1998).

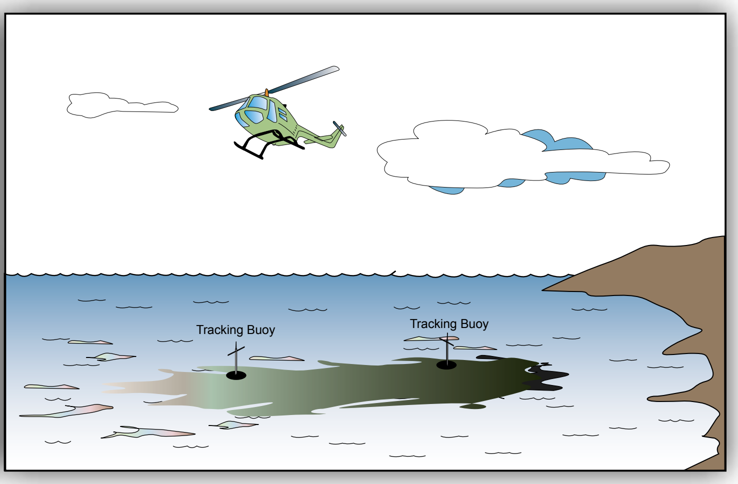
Tracking buoys may be used to follow an oil slick as it moves with winds, surface currents and ice movements. The buoys are released into an oil slick, where they move with the oil and ice, transmitting data on the location and movement of the slick.

Satellite imagery may be available to provide real-time images of ice conditions and possibly oil slicks. Satellite images may lack the resolution necessary to detect small oil slicks directly, but in combination with tracking buoys, satellite imagery can be used to develop a picture of the ice conditions in the vicinity of the oil. After the Deepwater Horizon blowout, satellite imagery of the spill was used to estimate the spill size and track the movement of major oil slicks (SkyTruth 2010).

Airborne reconnaissance may be conducted using a range of technologies, including visual observations and still and video cameras or remote sensing using infrared and ultraviolet sensors, laser fluorosensors and radar (Fingas 2001). Trained visual observers can be teamed with remote sensing technologies to identify oil slicks, although it is often difficult to distinguish between oil slicks and other factors such as silt on ice, cloud shadows on water, and wind patches, which may appear similar to oil. Visual observations may also be used to track oil and ice position and movement. Still and video cameras may be deployed from a response vessel or dedicated surveillance vessel and can record overall spill locations and slick boundaries in reasonable light conditions. The accuracy of visual observations from vessels may be limited by visibility factors.

Figure 5-2. Oil Spill Tracking and Surveillance Methods in Arctic Ocean—Tracking and surveillance methods in use or proposed for use in the Arctic include surveillance from aircraft or vessels using remote sensing or visual observation methods (below left), using trained dogs to sniff oil under solid ice (opposite page), or deploying tracking buoys into oil that is floating on the surface or amid sea ice (below right).





A 2010 study found that detecting isolated patches of oil amid sea ice is a major challenge to all existing technologies and that darkness, low clouds and fog limit tracking and surveillance methods regardless of ice conditions (Dickins *et al*. 2010).

On-ice surveys may be used on solid ice that is thick enough to support personnel and equipment. Handheld GPS units may be used during on-ice surveys to document the location and extent of spills in conjunction with spill survey activities, but these are limited by ice thickness and are typically inefficient, requiring significant time and manpower. Under-ice lights, slots, trenches, bore holes (holes that are bored or drilled into the ice to see whether there is oil underneath) and other techniques may be used to identify and track ice location and movement. All of these techniques are time-consuming and are best applied when responders have a basic idea about where under-ice oil may be located. Remote sensing technologies have also been tested to track oil under ice, and researchers have used specially trained dogs to detect oil under ice using their olfactory senses. Under-ice tracking with equipment or dogs can be time-consuming, and the logistics of transporting them by air and over icy terrain may cause stress (Dickins *et al.* 2010).

Trajectory models may also be used to map or predict the movement of oil if it cannot be tracked using other surveillance techniques. In open water, surface oil trajectories are developed based on the wind speed and direction and the current. Predicting the movement of oil under ice or within ice flows can be more complicated. As discussed in Section 4.1.3, existing oil spill trajectory models cannot accurately predict how oil and ice interactions will affect oil movement when sea ice is present (Khelifa 2010).

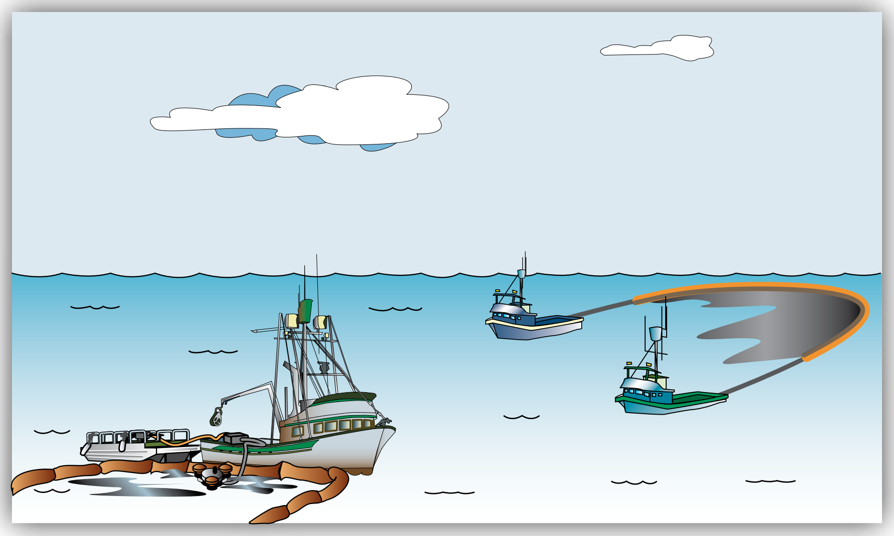
A 2010 study that compared various technologies for remote sensing of oil in ice found that a flexible combination of sensing methods that can be operated from a variety of platforms should be available for oil spill tracking in Arctic seas (Dickins *et al.* 2010). All airborne sensing systems were affected by clouds, fog or darkness, with the exception of side-looking airborne radar (SLAR). Although SLAR showed the most promise for slicks in very low ice concentrations, the presence of grease ice made oil indistinguishable from ice. In close pack-ice conditions (above 60 percent ice coverage), GPS tracking buoys were found to be the most effective tool. For oil trapped under solid ice, ice-sniffing dogs and ground-penetrating radar (GPR) were the most promising options. The study found that detecting isolated patches of oil among tightly packed floes of sea ice is a major challenge to all existing technologies, and that the presence of darkness, low clouds and fog limits most tracking and surveillance methods, regardless of ice conditions (Dickins *et al.* 2010).

5.3.2 Mechanical Recovery Methods

Mechanical recovery of oil spilled on water involves the physical containment of the oil and the subsequent removal of the oil from the surface. Mechanical recovery of oil spilled in the Arctic Ocean can be conducted only during open-water or broken-ice conditions. Once oil is trapped under pack ice, the on-water mechanical recovery methods discussed here are no longer a viable option until the ice breaks up. The objective of mechanical recovery is to concentrate oil to a thickness that will permit recovery.

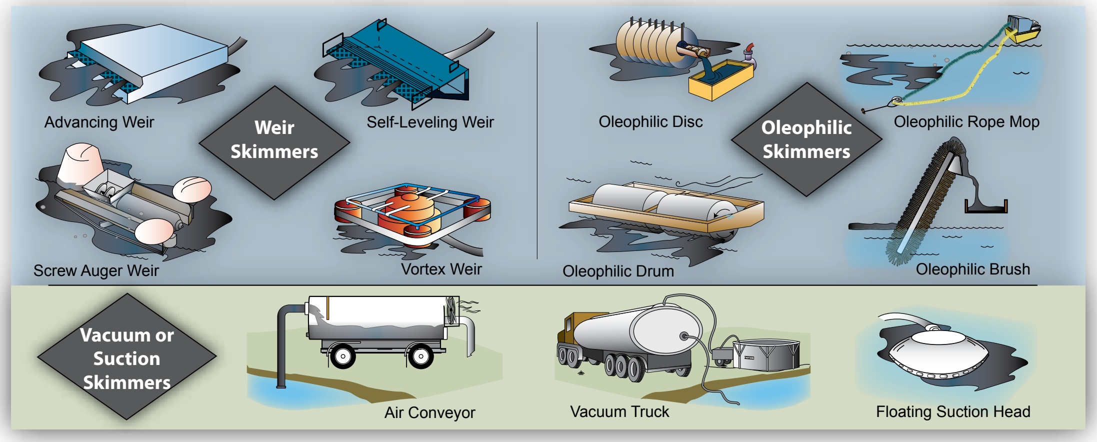
Mechanical recovery systems have three major components: containment barriers, recovery systems, and storage for recovered oil and water. Mechanical recovery systems are supported by additional equipment and resources such as vessels, pumps, anchors, decanting (oil/water separation) systems and trained personnel (Figure 5-4).

Figure 5-3. Typical On-Water Mechanical Recovery System—On-water mechanical recovery operations involve containing oil to an appropriate thickness and then removing it from the water surface using skimmers. On-water mechanical recovery is viable in open water and in some low ice concentrations and would be applicable in the Arctic Ocean only a few months of the year.



A boom is the most common type of on-water barrier used to intercept, contain and concentrate spreading oil. Booms come in a variety of forms and may be deployed in a number of configurations. Sea ice may act as a natural containment barrier under certain conditions, but typically the presence of sea ice is an impediment to response. Recovery of oil contained or concentrated with booms or natural barriers is accomplished using a skimming or recovery system that removes oil and water from the surface and transfers the recovered liquids to temporary storage, where the oil and water can eventually be separated for disposal. As with booms, there are many models of skimmers (Figure 5-5).

Figure 5-4. Skimmers—There are three main types of skimmer design. Weir skimmers (left) draw liquid from the surface by creating a depression in the water into which oil and water pour and are then pumped to storage. Oleophilic (oil-attracting) skimmers (right) use surfaces such as rotating discs, brushes or drums to pick up oil adhered to a collection surface, and the oil is then scraped from the collection surface and pumped to a storage device. Suction skimmers (bottom) use a vacuum to lift oil from the surface of the water. Weir and suction skimmers may collect a large proportion of water with the recovered oil. Most suction skimmers are mounted on trucks and work best on land.



Skimmers operating in the marine environment may be stationary, meaning they are dropped into a pool of oil to recover it (Figure 5-6). They may also operate in an advancing mode, in which they are slowly moved through an oil slick. In either mode, the effectiveness of the skimmer relies on its ability to encounter oil at sufficient thickness to remove it. Mechanical recovery may be limited if the encounter rate—the rate at which a skimmer comes into contact with pooled oil—is not sufficient to allow for effective skimming. Factors that may limit the encounter rate include the speed of the skimmer through the water (above very low speeds, the skimmer may not work) and failure to contain and concentrate the oil to the required thickness, which would happen if the boom was not effective. Ice and other debris can clog the skimmer or prevent it from encountering and recovering oil. They also can cause the boom to tear or at higher concentrations can prevent some vessels from safely deploying booms or skimmers.

Figure 5-5. Stationary Deployment of a Weir Skimmer During Training Exercise *(Photo Credit: Sr. Airman Jonathan Steffen/U.S. Air Force)*—Sea ice complicates skimming operations, including positioning of the skimmer. Skimmers typically work best in open-water conditions where there is no ice. Skimmers work poorly during fall freeze-up conditions when ice is first beginning to form and is more slushy.

On-water mechanical recovery technologies are significantly less efficient when sea ice is present (Abdelnour and Comfort 2001). Sea ice in its various forms affects the functionality of booms, skimmers and vessel operations and may limit or preclude the ability to operate certain classes of vessels. Cold-weather conditions can further complicate mechanical recovery.

The presence of sea ice interferes with containment of oil in sufficient thickness to recover it. Oil tends to disperse and mix into the ice, creating an additional step for responders trying to separate the oil from the ice. Sea ice may reduce the effectiveness of containment booms by interfering with the boom position, allowing oil to entrain or travel under the boom or causing the boom to tear or separate. Sea ice may also reduce a skimmer's efficiency in recovering oil by lowering the encounter rate and increasing the time needed to position the skimmer for optimum recovery among ice floes (Abdelnour and Comfort 2001, Fingas 2004). Marine operations in sea ice are vulnerable to rapid changes in weather and ice conditions, and significant down time often occurs because of the movement of ice in response to wind conditions and sea state (Dickens and Buist 1999).

Although sea ice coverage generally complicates on-water mechanical recovery, increasing ice concentrations may help contain oil under certain conditions. Dickins and Buist (1999) found that ice concentrations of 60 percent or higher provide "an effective means of reducing oil spill spreading." Although the spreading rate is diminished, the recovery rate can be severely affected by responders' inability to access the oil because of weather, visibility, or vessel, mechanical and human limitations. Higher ice concentrations make recovery operations extremely difficult because of limits to vessel operations.

In ice concentrations below 60 percent, additional containment is usually required to concentrate the oil so that it can be recovered by mechanical skimming devices. Dickins and Buist (1999) found that most containment booms can be used in light brash ice conditions and ice concentrations up to about 30 percent. Based on these estimates, ice conditions ranging from 30 percent to 70 percent coverage may present the biggest challenge to mechanical response, because conventional booms are likely to be ineffective and ice conditions are not sufficient to contain the oil (Evers *et al.* 2006, Glover and Dickens 1999).

Figure 5-6. Ice Interfering with Mechanical Recovery Equipment during Sea Ice Response Trials in the Alaskan Beaufort Sea in 2000 *(Photo Credit: Kirsten Ballard, ADEC)*—A series of field trials conducted in the Beaufort Sea during the spring and fall ice seasons in 2000 demonstrated that the maximum operation of the barge-based recovery system in sea ice conditions was zero to 1 percent in fall ice, 10 percent in spring ice without ice management, and 30 percent in spring ice with extensive ice management (NRC 2003b). The images at right, in which ice conditions were estimated at 10 percent coverage or less, show how relatively low ice concentrations can interrupt mechanical recovery because of sea ice interfering with the skimmer (top left) or boom (bottom left), or causing the boom to fail (right).

5.3.3 In-Situ Burning

Like mechanical recovery, in-situ burning is a response option that is available only when oil is floating on the surface of open water or amid broken ice. Oil that has pooled on the surface of pack ice may be available for in-situ burning during spring melting, but oil trapped below pack ice through the winter cannot be accessed for burning.

In-situ burning of spilled oil on the water's surface involves a controlled burn of floating oil that is contained to the appropriate thickness (1 to 3 mm for fresh crude, more than 3 mm thick for weathered crude oil). The oil is ignited by releasing a burning, gelled fuel from a helicopter onto the oil or by releasing an ignition device from a vessel or other access point. If successfully ignited, some of the oil will burn off the surface of the water or ice, but some residual nonvolatile compounds will remain. This residue may float, sink or be neutrally buoyant, depending upon the type of oil spilled and the conditions of the burn (Brandvik *et al.* 2010a).

As in mechanical recovery, oil containment for in-situ burning can be accomplished with natural barriers (topographic features on land, snow berms, sea ice) or man-made booms. However, fire booms used for in-situ burning must be constructed of fire-resistant materials. Response vessels may tow fire booms in a U-shaped configuration that is also commonly used during mechanical response (Figure 5-8). Alternatively, oil may be encircled in a stationary fire boom or pooled in ice leads and burned.

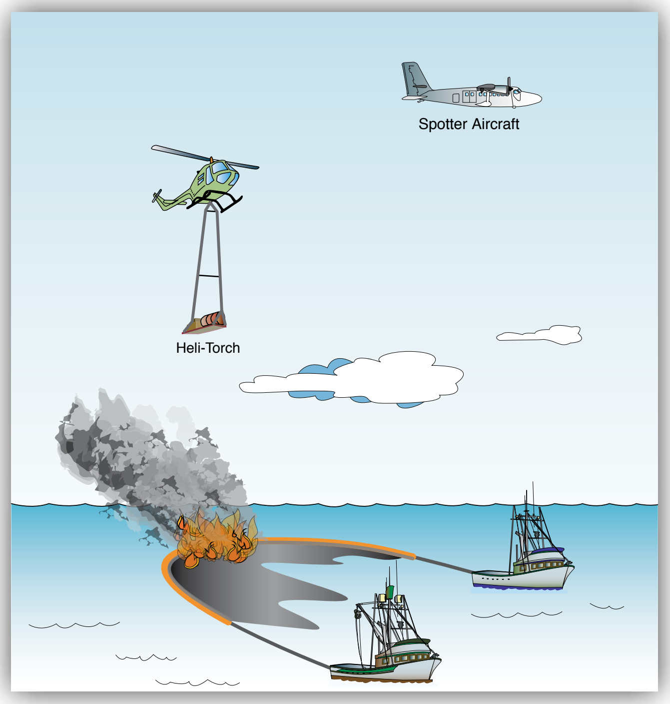


Figure 5-7. Typical On-Water In-Situ Burning Operations.

Successful ignition and burning require adequate slick thickness for ignition, minimal wind and waves, and oil that has not emulsified (incorporated water) too much. The more weathered the oil, the thicker it must be to burn (Brandvik *et al.* 2010a). If a burn is inefficient, a mixture of unburned oil, burn residue and soot will form (NOAA 2005). Downwind emissions must be below threshold levels for sensitive populations (NRT 1997). Chemical herders, currently under development, may thicken a slick to allow for ignition (Buist *et al.* 2006, Buist *et al.* 2010a and 2010b).

The in-situ residues that remain after a burn have characteristics and behavior that depend on the chemical composition and physical properties of the parent oil, the state of weathering and the oil slick thickness (Buist *et al.* 1997).

The results of in-situ burning differ from mechanical recovery in that the oil is not completely removed from the environment. The by-products of in-situ burning include air emissions (Figure 5-9) and burn residues, and the process of burning creates heat at the air-water interface. All of these factors have potential environmental and ecological consequences.

The smoke plume presents a number of response challenges, from predicting the contents and movement of the plume to assessing and communicating the human health and environmental toxicity risks posed by the emissions. Soot from an in-situ burn plume may coat sea ice and snow cover.

Although a number of scientific studies have confirmed that the residues that remain after in-situ burning are less toxic than the original oil, burn residues are not completely benign and should be removed from the marine environment whenever possible (API 2004). Burn residues may float or sink, and they sink only after they have cooled. Residues from burns of thicker slicks of heavier crude oils (both fresh and weathered) are more likely to sink than are burn residues from lighter oils (S.L. Ross 1998). Research also indicates that crude oil burn residues are generally denser than their parent oils and that residue density is related to the density of the parent oil, the state of weathering, and the slick thickness (Buist *et al.* 1997).

Figure 5-8. Smoke Plume from In-Situ Burn Test *(Photo Credit: MMS)*.

Floating burn residue may be picked up with large strainers, nets or hand tools, with viscous-oil sorbents, or with standard viscous-oil skimmers; however, this is a very time- and labor-intensive process. Floating residues can be stranded, much as floating oil slicks can, along shorelines or other coastal features, but because of their thick consistency, they can be difficult to remove using conventional shoreline response technologies. Floating residues may be ingested by fish, birds and marine mammals and may also foul gills, feathers, fur or baleen (Shigenaka and Barnea 1993). The presence of sea ice makes tracking and recovering burn residues more challenging. There are no published accounts of in-situ burning operations in broken ice during an oil spill.

Burn residues that sink to the bottom are far more difficult to recover. In 2002, the American Petroleum Institute (API) published a study that investigated the potential for residues to sink after an in-situ burn of spilled oil. The researchers identified the need for recovery of sinking burn residues and recommended suspending a net along the bottom of the containment boom across the apex of the burn area to catch the residues as they begin to cool and sink. To date, no new technologies for recovering sunken in-situ burn residues have been reported in the literature. The recovery of sunken in-situ burn residues in broken ice conditions has not been well studied.

Sunken residues can threaten benthic communities, adversely affecting resources that would not otherwise be affected by an oil spill at the water surface. They may be ingested by benthic feeding organisms, including fish, shellfish or marine mammals. During the Haven spill in Italy in 1991, approximately 3 million gallons of oil was burned, and the residues sank and were distributed over an area of the seabed approximately 55 square miles in size. These residues adversely affected local trawl fisheries because the fishermen feared they would foul their gear (Martinelli *et al.* 1995). Although trawling fisheries do not exist in the U.S. Arctic Ocean, many species live on the seabed and would be negatively affected by sunken oil residues. Publicly available documentation from the Deepwater Horizon spill does not specify whether in-situ burning residue recovery operations were undertaken to remove the oily residues left behind from the multiple burns.

In-situ burning can also affect the surface micro-layer, which is approximately the upper few-hundredths of an inch of the water surface. The surface micro-layer is an important ecological niche that provides habitat for many sensitive life stages of marine organisms. Eggs and larval stages of fish and crustaceans and reproductive stages of other plants and animals develop in this layer, which often contains dense populations of micro-algae with distinct species compositions from the phytoplankton in the layers below (Shigenaka and Barnea 1993).

Surface micro-layer organisms are vulnerable to oil slicks, but the effects do not seem to be intensified by burning. Experimental data from a large offshore burn showed that water temperature did not increase during burning, despite the intense heat generated by the burn (Fingas *et al.* 1994). To date, no published studies address the potential impact of in-situ burning on the surface micro-layer in polynyas.

Numerous published articles and reports refer to the potential use of in-situ burning in sea ice conditions. The reduced efficiencies of mechanical recovery are frequently cited as a rationale for in-situ burning in ice leads. In-situ burning is also considered a viable option for treating oil on top of solid ice or oil that pools on top of melting ice in the spring (Solsberg 2008). The general consensus is that leads in broken and pack ice provide an opportunity for in-situ burning, because the ice acts as a natural containment barrier to the slick and the open water in the lead provides the necessary access. However, responders must also have access to ice class vessels and/or air support to carry out these operations.

Before the Deepwater Horizon oil spill, in-situ burning had not been widely used, particularly in cold climate on-water spill response, so the body of information regarding in-situ burning in Arctic regions is based primarily on experimental data. The presence of sea ice appears to slow the rate of in-situ burning and create slightly larger quantities of residue than occur in open water (Fingas 2004, Buist *et al.* 2003). However, in-situ burning studies in slush ice showed efficiencies as high as 50 percent for weathered crude oils and 80 percent for fresh oil (Buist *et al.* 2003).

Burn efficiencies cited in laboratory studies (e.g. the 50 percent cited in Buist *et al.* 2003) may not be duplicated in most field conditions, because burn studies involve pouring oil into a containment area to the required thickness, rather than having to corral the oil under field conditions in which vessels and fire booms must be able to operate. It is also important to recognize that burn efficiency rates describe the percentage of the corralled oil that is burned off, rather than the percentage of the total spill amount that is treated. For example, the in-situ burning operations after the Deepwater Horizon blowout reportedly included some highly efficient burns, yet burning was estimated to treat only 5 percent of the total spill amount. In the Arctic Ocean, even if individual burns removed 50 percent of oil present in a burn area, they might treat only a very small percentage of the oil spilled, leaving most of the total spill volume in the environment.

As with mechanical recovery, the effectiveness of in-situ burning is related to the percentage of ice coverage. Both techniques face particular challenges in slush or grease ice; burn efficiencies in the presence of slush ice are lower than in open water and leave behind more residue (Buist *et al.* 2003). The major difference between mechanical recovery and in-situ burning in ice is that the natural containment provided by ice floes at higher ice concentrations may be conducive to in-situ burning if ignition can be attained. At ice coverage up to about 30 percent, in-situ burning generally requires the use of man-made fire booms to contain the oil to the desired thickness. Because of this, in-situ burn operations face many of the same constraints as mechanical recovery. Boom-towing vessels must be able to maneuver and position booms to contain the oil to the desired thickness, and an ignition source must be deployed from a vessel or aircraft.

When ice coverage is above 60 or 70 percent, in-situ burning may be accomplished using the ice floes as natural containment. In this case, the ignition source will probably be from an aircraft, unless icebreaking or ice-reinforced vessels are available and capable of maneuvering in the vicinity of the spill. Ice conditions in the 30 percent to 70 percent range are considered to be the "most difficult from an in-situ burning perspective" (Evers *et al.* 2006). In this range, natural containment by the ice is less likely, and containment boom deployment is generally not possible.

Research into the use of herding agents—chemicals used to improve slick thickness—is ongoing, with a focus on use of herding agents in the presence of sea ice (Evers *et al.* 2006, Buist *et al.* 2010a and 2010b).

In-situ burning relies on good visibility and weather. In-situ burns cannot be ignited when visibility conditions or darkness preclude flight operations.

5.3.4 Dispersants

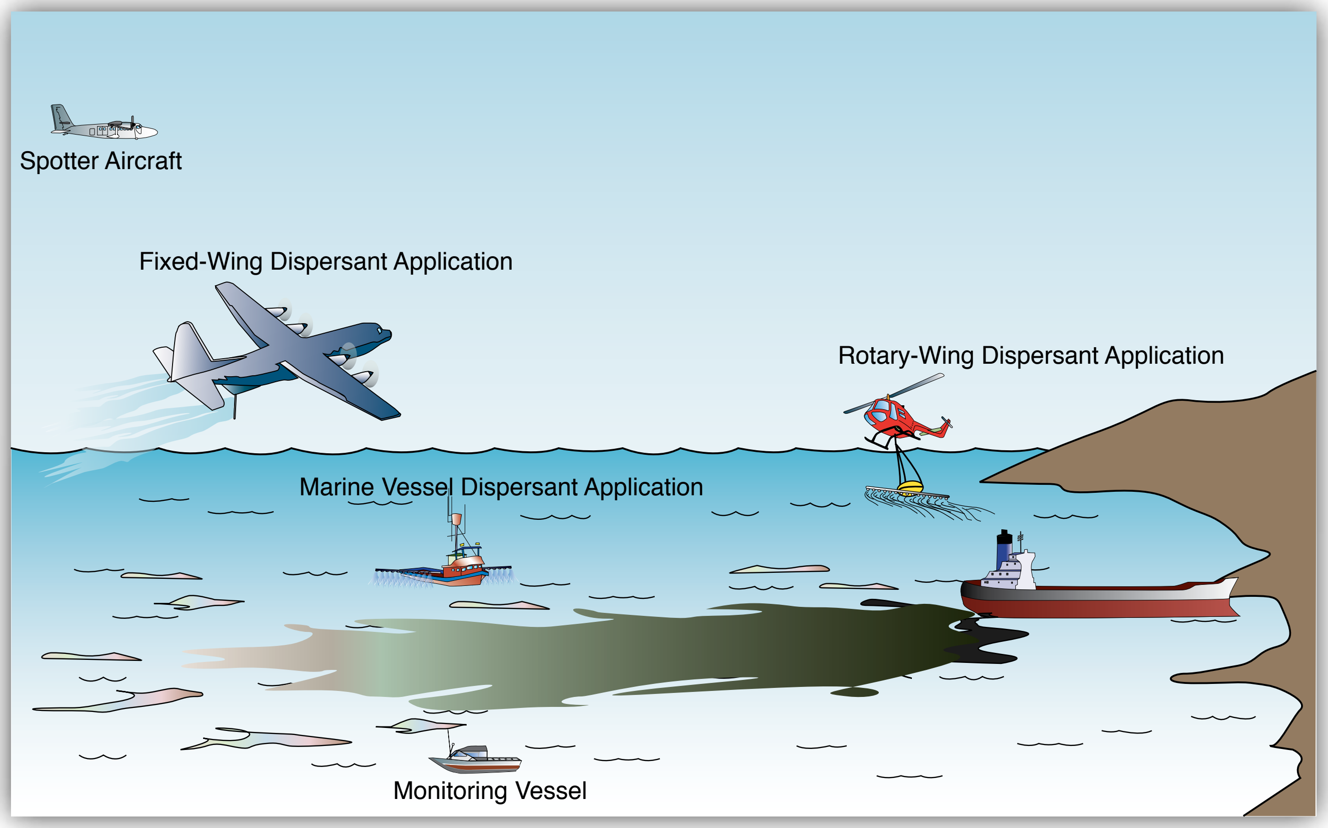
Dispersants are typically selected as a response technique because, although they do not physically remove the oil from the water, they may break up oil slicks and reduce the amount of oil that reaches and contaminates shoreline areas. Chemical dispersants have been the subject of significant research over the past decade, much of it focused on cold-water and Arctic applications (Evers *et al.* 2006). However, substantial scientific and technical work still must be done before dispersants can be considered a practical response tool for the Arctic. Under the spill response framework established by the joint state/federal Alaska Regional Response Team, there is no pre-approval for dispersant use in the U.S. Arctic Ocean. Therefore, most discussion of dispersant use in the U.S. Arctic Ocean is theoretical.

Many questions remain about the efficacy of dispersants in Arctic waters, the potential toxicities, and the operational feasibility of applying dispersants in ice-infested waters.

Dispersants are chemicals sprayed or applied onto oil slicks to accelerate the dispersion of oil into the water column. The chemical mixtures contain three components: surfactants, solvents and additives. Surfactants are molecules with an affinity for two distinct liquids that do not mix, acting as an interface between them. One part of the surfactant molecule used in dispersants has an attraction to oil (i.e. it is oleophilic) while another part has an attraction for water (i.e. it is hydrophilic). Dispersants promote the formation of tiny oil droplets in the water column and prevent the re-coalescence of droplets into slicks.

Dispersants do not actually remove oil from the water but are intended to limit the amount of oil forming a slick on the water surface or shoreline by breaking the oil into smaller droplets. Dispersants are applied using spray nozzles, pumps and hoses and can be applied from a vessel or aircraft (Figure 5-10). Dispersant operations are usually monitored from aircraft to make sure that the application is on target. They have a limited time frame for effective application, requiring a prompt, accurate application of the chemicals, with the oil type, emulsification, salinity, weather conditions and sea state all aligned. Recently, there has been research into new dispersant application systems designed for use in Arctic conditions (Daling *et al.* 2010)

Figure 5-9. Typical Dispersant Application and Monitoring Operations.



After the Deepwater Horizon blowout in the Gulf of Mexico, substantial amounts of dispersants were applied underwater to the oil as it escaped from the well. This type of application appears to have been a novel approach, because no published studies or spill response plans for U.S. oil exploration or production operations discuss subsea dispersant application. Current U.S. dispersant application monitoring protocols address above-water application only (U.S. Coast Guard *et al.* 2006).

The use of dispersants in Arctic waters presents a special set of considerations and concerns (Figure 5-11). Reduced water temperatures, variations in salinity, and the presence of sea ice can all affect dispersant effectiveness. However, the slowed weathering of oil under Arctic conditions may be viewed as extending the window of opportunity for dispersant use (Daling *et al.* 2010).

Figure 5-10. Dispersants being applied from the air, left. The U.S. Arctic presents another set of challenges, such as the presence of sea ice, below *(Photo Credits: USGS).*

Researchers at the National Marine Fisheries Service Auke Bay Laboratory in Juneau, Alaska, reported on laboratory effectiveness tests that examined the dispersibility of Alaska North Slope crude oil under a combination of sub-Arctic salinities and temperatures. Their results showed that the dispersants tested, Corexit 9500 and Corexit 9527, had an effectiveness of less than 40 percent for fresh oil and less than 10 percent for weathered oil. The researchers concluded that "at the combinations of temperature and salinity most common in the estuaries and marine waters of Alaska, effectiveness of dispersants was less than 10 percent." They cautioned, however, that these results are based on laboratory studies performed at low mixing energy (Moles *et al.* 2002). The results contradict an earlier study by S.L. Ross (1998), which concluded that "if used properly, Corexit 9527 should be reasonably effective on spills of Alaska North Slope crude in Prince William Sound or the Gulf of Alaska."

Dispersant toxicity is also an issue that weighs into response decision-making, particularly in Arctic environments, which may be slower to recover from exposure to toxic chemicals. Chemically dispersed oil has been demonstrated to be more toxic to some marine organisms than untreated oil (Fuller and Bonner 2001, Singer *et al.* 1998, Gulec and Holdway 1997). Researchers have also found that the undispersed oil residue after a dispersant application may be more toxic than the untreated oil (Lindstrom *et al.* 1999).

The toxicity of chemically dispersed oil may be enhanced by exposure to sunlight (Barron 2000). Chemical dispersion of oil has been shown to enhance oil uptake and bioaccumulation (Wolfe *et al.* 1997). Direct exposure to misapplied dispersant can harm birds and mammals (NRC 1989). No studies to date consider the toxicity of dispersed oil to marine mammals, either directly or through uptake of contaminated food.

Despite ongoing studies, the general consensus in the spill response community is that dispersants are not a proven technology for use in most sea ice conditions (Evers *et al.* 2006). A review of dispersant use in oil spill response conducted by the National Academy of Science recommends additional studies on the physical and chemical interactions of oil, dispersants and ice before dispersants can be considered a mature technology for use in sea ice (OSB 2005). A report on oil spill response technology in ice-covered waters recommends additional study into the potential use of dispersants in sea ice, including the potential use of icebreaking vessels to add mixing energy, which is the energy required to mix dispersants with surface oil so that they work as intended (D.F. Dickins Associates 2004).

More dispersants were used in the Deepwater Horizon spill response than on any previous spill. Unlike most spills and published studies, in which a single dispersant is used, the Deepwater Horizon response involved combinations of several dispersant chemicals. Studies are ongoing on the impacts of dispersant use on species and the synergistic effects of multiple dispersant formulations mixed together and with oil in the marine ecosystem. The subsea application of dispersants during the Deepwater Horizon spill also represented a significant variance from typical dispersant use. Additional study is needed to determine whether subsea dispersant use is in fact a viable response tactic and to consider the efficacy and the environmental impacts of applying dispersant chemicals to a subsea release.

Use of dispersants is also limited by environmental conditions and weather. Aerial application of dispersants requires low winds and good visibility, and dispersants cannot be applied during periods of darkness. The damping effect of sea ice reduces the mixing energy necessary for dispersants to work as intended.

5.4 Research and Development to Improve Oil Spill Response in Arctic Waters

The need to improve mechanical recovery capabilities in sea ice is cited repeatedly in the published literature (Abdelnour and Comfort 2001, Dickens and Buist 1999, Fingas 2004). This poses a significant research and development challenge, because oil leasing, exploration and production in the Arctic are outpacing oil spill response technologies, particularly in sea ice. A 2004 report prepared for the Prince William Sound Oil Spill Recovery Institute and the U.S. Arctic Research Commission (D.F. Dickins Associates 2004) identifies a need to "expand the operational capability of existing spill response equipment to enable oil recovery in ice." The same document indicates a "low" confidence in the ability to improve mechanical response in ice, noting "improvements likely to be incremental, resulting in modest increases in recovery effectiveness."

Recent research and development focused on improving oil spill response in ice has considered the use of oil deflection systems, which apply technologies such as air jet blowers, propeller wash, booms, belts, plates or small "curtains" of water bubbles to redirect the flow of oil into a collection area while moving ice in a different direction (D.F. Dickins Associates 2004). Researchers in Finland have developed oil spill response devices for sea ice conditions that may be attached to the bow of a vessel and include a combination of ice-processing belts and skimming systems (Rytkonen *et al.* 2003).

Although there have been incremental improvements in individual skimming technologies, there have been no breakthrough technologies reported in the literature that would significantly improve mechanical recovery in sea ice. One skimming technology that has shown some promise is a brush drum skimmer that can be deployed from a hydraulic arm on a response vessel, because of its ability to recover oil from pools in ice. In general, the use of skimmers in ice is considered more appropriate for "batch" removals, focusing on small pockets of oil, than for recovery of oil from a major blowout (BPXA 2003).

5.4.1 Joint Industry Program on Oil Spill Response for Arctic Waters

In 2006, a Joint Industry Program (JIP) on Oil Spill Response for Arctic and Ice-covered Waters was initiated with funding from several major international oil companies and research by consultants, academicians and a few national agencies. A team of researchers from SINTEF, a large Norwegian research organization that is active in oil spill response technologies research and development, led the JIP efforts. The purpose of the JIP, which was completed in 2009, was to improve "oil spill response techniques for Arctic waters" through a combination of laboratory and field trials, and to gather more knowledge about the fate and behavior of oil spills in ice and cold water temperatures (Sorstrom *et al.* 2010). JIP was funded jointly by SINTEF, the Norwegian Research Council, and seven major oil companies; there was no public participation in or review of the JIP published findings.

The JIP experiments focused on aspects of in-situ burning, dispersant use, and mechanical recovery in various sea ice conditions and also looked at remote sensing and tracking technologies and physical and chemical processes associated with oil weathering in Arctic waters. The program culminated in a series of field experiments during 2008 and 2009 in the Norwegian Barents Sea. Results from the JIP are summarized in a synthesis report (Sorstrom *et al.* 2010) and in a series of technical reports presented at technical conferences.

The reported findings from the JIP paint an optimistic picture of the potential applicability of several technologies to Arctic oil spills. The overwhelming emphasis of the program appears to have been on nonmechanical technologies. Of the eight papers presented on JIP studies during the 2010 Arctic Marine Oil Pollution (AMOP) Technical Seminar sponsored by Environment Canada, four dealt with in-situ burning technologies (Buist *et al.* 2010,b Potter and Buist 2010, Brandvik *et al.* 2010b, Brandvik *et al.* 2010c), one with dispersant application (Daling *et al.* 2010), two with oil-water interactions and weathering (Faksness *et al.* 2010, Brandvik *et al.* 2010a), and one with remote sensing (Dickins *et al.* 2010). No papers were presented on mechanical recovery, which is the only preapproved oil spill response technique for the U.S. Arctic. The JIP final report presents a brief discussion of the mechanical recovery testing program, which focused only on skimmer technologies and resulted in the identification of two skimmer designs, modifications of typical open water-skimmers with the addition of ice processing mechanisms that show "promise" for Arctic application (Sorstrom *et al.* 2010).

The JIP was a first step toward more rigorous study of oil spill response technologies under Arctic conditions, and the inclusion of field testing, in which small oil spills were released among sea ice for the purpose of experimentation, adds a field element to the experiments. However, the studies were conducted under controlled conditions, at preselected times and locations where researchers had ready access to the area and were able to pre-position the needed resources to conduct the experiments as planned (Figure 5-12). This distinction is relevant to any attempts to draw real-world planning assumptions based on the reported study results, because application of these technologies, should they become market-ready, will be subject to a wide array of potential logistical and operational constraints that could significantly reduce or preclude their applicability.

Figure 5-11. SINTEF JIP Controlled Study with Pre-Positioned Booms and Response *(Photo Credit: SINTEF).*

Several JIP studies considered oil-ice weathering as it affects the window of opportunity to use nonmechanical response technologies (in-situ burning and dispersants). They found generally that the slower weathering and degradation of oil spilled in ice-infested waters may extend the period during which the oil is ignitable and/or dispersible.

The chemical herder studies focused on the use of chemical herding agents to thicken oil spills when sea ice is present in order to facilitate in-situ burning. This concept has been a subject of substantial research over the past several years, indicating a strong interest on the part of the oil industry to develop in-situ burning for use in Arctic oil spills. Chemical herders are sprayed onto the water surrounding an oil slick to form a thin layer of surfactants on the water surface, reducing the surface tension of the surrounding water. When the surfactant layer reaches the edge of a thin oil slick, it changes the chemical balance that caused the oil to contract and fold against itself and serves to form thicker layers over a smaller area. The application to response involves thickening the slick to the point where it will support ignition and burning.

During the JIP field study, two experimental burns were conducted on chemically herded oil slicks in pack ice. The researchers report that 80 percent of the oil was burned in the first application, a 26-gallon oil slick, and 90 percent in the second experiment, a164-gallon oil slick (Buist *et al.* 2010b). Although these results confirm that chemically herded oil slicks are indeed combustible, a number of considerations must be made when these results are extrapolated to the real world. For example, in the second application, in which 90 percent of the oil was burned, chemical herders were applied 15 minutes after the slick (fresh crude oil) had been released to the pack ice. Boats were standing by to surround and spray the slick. The fresh oil was easily accessed because there was no need to track it, travel to it, or mobilize the equipment needed to apply the herder and ignite the oil. The experiment demonstrated that chemical herders work, but to jump from such a small, controlled field exercise to assumptions about real-world spill response may be premature.

The JIP dispersant tests report focuses on new application technologies to apply chemical dispersants to small pockets of oil in sea ice, reporting that the application system resulted in highly efficient dispersant application. Because sea ice dampens wave activity, which is required for dispersants to mix with oil and work properly, propeller wash from boat engines was used to add mixing energy. Interpretation of the results is subject to the same types of considerations discussed for the chemical herder studies; real-world logistical and operational constraints were not present during the field trials.

The JIP program was an important step forward in researching oil spill response technologies for use in Arctic waters. The results, however, are subject to interpretation before assumptions can be made about the applicability of the technologies to spill response in the Arctic. For example, the two skimmer models looked at the recovery efficiencies of these skimmers deployed under controlled ice conditions, with ready access to pooled oil. The other components of an on-water recovery system—the booms required to contain the oil, the vessels required to operate the booms and skimmers, the on-water storage for recovered oil, and the overarching spill response system required to support major on-water response operations—would still prove daunting. Even if the skimmer efficiencies are extremely high, there may be days or weeks during which the skimmers cannot be deployed because conditions are too rough, windy, foggy or dark (See Chapter 6 of this report).

5.4.2 Field Exercises and Oil Spill Drills in the U.S. Arctic Ocean

Most of the published studies on oil spill response in Arctic waters focus on the use of specific techniques or technologies under a range of ice conditions (Figure 5-13). These studies are often conducted in a laboratory or small test tank. Field testing is less common, and most field trials involve artificial controls of weather or ice conditions, or use only one or two components of a spill response system. Although such studies are valuable to improve empiric knowledge of how response technologies function, their results must be viewed with caution when applied to a full-blown spill response in the Arctic Ocean.

Figure 5-12. Example of Tank Test for Mechanical Recovery of Oil Spilled in Sea Ice *(Photo credit: Nuka Research)*—During wave tank tests, ice is typically frozen under controlled conditions to the desired thickness and concentration, and various technologies are tested. The ice is then combined with oil in tanks of various sizes to test equipment. At left, ice was created in tanks at the U.S. Army Cold Regions Research and Engineering Laboratory and used in a series of skimmer tests.

The terms trial, exercise, and drill are often used interchangeably, yet all three are different types of field tests. Field trials, like the JIP, are experiments that, though conducted in the field, involve controlled conditions and significant pre-planning and are typically research and development efforts focused on getting detailed data on a few components of a spill response system, rather than exercising the entire system. Field exercises are planned field tests where actual responders practice the deployment of spill response equipment under real-world conditions. Exercises are valuable for training and practice, and may generate information about how response equipment functions and the limits to response systems posed by real-world conditions. But exercises, like field trials, have an inherent artificiality in that the equipment, vessels, and personnel that participate are pre-notified and often pre-positioned before the exercise occurs. A true spill response drill, on the other hand, tests the ability to put the response system together in the first place. During an unannounced drill, an operator will be required to demonstrate the response capacity that is described in its oil spill contingency plan, by contacting, mobilizing, and deploying all or part of their spill response system.

The primary differences between the field trials conducted during the JIP and other types of field exercises or drills is typically one of scale—drills and exercises are practical endeavors that test the entire system to various degrees and may involve mobilizing, deploying, operating and demobilizing sets of equipment and personnel that would carry out one of more response functions. Field trials typically evaluate the performance of an isolated technology or piece of equipment under various conditions. A field trial is more akin to a laboratory study than to a true drill or exercise. The Joint Industry Program (JIP) included a series of field tests conducted in the Barents Sea in 2009, during which a variety of tactics and techniques were tested in the field under controlled conditions. The results of these studies provide important empirical data that contribute to rules of thumb for using these techniques under a range of ice conditions, oil weathering and other factors. However, these trials were not full-scale field deployments, because they tested only certain components of a response system.

Drills and exercises typically occur well after a field trial or research and development program has been completed. For example, while the JIP field trials looked at two specific skimmer designs and tested those skimmers in a controlled area to measure their recovery capacity, the 2000 Beaufort Sea field exercise in Alaska deployed skimmers, boom, multiple vessels, ice scouts and ice management and assessed the operating limits of the entire system. Both types of research and testing are important to furthering our understanding of oil spill response capabilities and limits in the Arctic, yet there have been few field exercises in the Alaskan Arctic Ocean.

A review of State of Alaska records shows that over the past decade, there have been four field exercises in which spill response equipment has been deployed in sea ice conditions and evaluated by state regulators. The first such exercise was the 2000 broken ice trials in the Alaska Beaufort Sea (Figure 5-14), where it was demonstrated that the actual operating limits for mechanical recovery systems—which are typically defined in the literature as being operable in up to 30 percent ice coverage—were closer to 10 percent. During fall freeze-up, ice conditions as low as 1 percent constituted the operating limit for a barge-based mechanical recovery system using conventional booms and skimmers (Robertson and DeCola 2001, NRC 2003a). A follow-up field trial testing the barge-based tactic, conducted in 2002, showed no major improvements (State of Alaska Senate Natural Resources Committee Hearing 2010)[2] and was followed shortly thereafter by the removal of that barge (the Endeavor) from the Alaska North Slope spill response equipment inventory. Two other field trials were conducted on the North Slope during open-water or broken-ice season, one in 2003 and one in 2009, but no reports were published documenting the lessons learned there.

Once the distinction between drills, exercises and field trials is understood, it becomes clear that it is not appropriate to extrapolate results from isolated field trials into expectations for a spill response. For example, in-situ burning tests conducted as part of the JIP showed that 98 percent of pooled oil can be burned in three-tenths ice coverage (Potter and Buist 2010). However, the oil was introduced into a pre-contained area at the desired thickness, then immediately ignited, and all vessels were on site and standing by. In the real world, the oil would have to be contained using fire booms or other barriers, and vessels would have to be able to navigate in and around the burn area, all before the oil became significantly weathered or emulsified. And even if the burn were extremely efficient and removed 98 percent of the oil within the containment area, the oil contained within that single burn might represent only a fraction of a percent of the total amount spilled.

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2 There is little written documentation from field trials in the U.S. Arctic Ocean since the 2000 broken ice exercises. A Freedom of Information Act request to the State of Alaska from Oceana yielded documentation that did not show that any subsequent tests had successfully deployed equipment under broken ice conditions.

components of a response system. It is not appropriate to extrapolate results from such trials into expectations for a spill response. For example, in-situ burning tests conducted as part of the JIP showed that 98 percent of pooled oil can be burned in three-tenths ice coverage (Potter and Buist 2010). However, the oil was introduced into a pre-contained area at the desired thickness, then immediately ignited, and all vessels were on site and standing by. In the real world, the oil would have to be contained using fire booms or other barriers, and vessels would have to be able to navigate in and around the burn area, all before the oil became significantly weathered or emulsified. And even if the burn were extremely efficient and removed 98 percent of the oil within the containment area, the oil contained within that single burn might represent only a fraction of a percent of the total amount spilled.

Figure 5-13. 2000 Broken Ice Exercise in Beaufort Sea *(Photo Credit: Kirsten Ballard, ADEC)*—Broken ice exercises were conducted in the U.S. Beaufort Sea during the spring and fall transitional ice periods in 2000. The exercises involved deployment of all vessels, booms, skimmers and ice management tactics that would be used for barge-based oil spill recovery in sea ice. The exercises tested the operating limits of the response system and found that skimmers clogged and booms failed at ice concentrations much lower than expected. This type of real-world deployment is critical to establish the operating limits of the components needed to clean up oil in ice-infested waters.

6 GAPS IN OIL SPILL PREVENTION PLANNING, RESPONSE CAPACITY AND OVERSIGHT IN THE U.S. ARCTIC OCEAN

In the best of conditions, recovering spilled oil is difficult. Spill response experts typically consider a response to be successful if 20 percent of the oil is recovered, and the cold and icy Arctic environment hampers the best technology available for spill response.

During the planning and permitting process for exploratory drilling in the Chukchi Sea in the summer of 2010, Shell Oil developed an oil spill plan and scenarios that contemplated how oil spill response operations in the U.S. Arctic Ocean might be conducted. The Minerals Management Service determined the proposed spill response system to be sufficient to clean up a well blowout of 5,500 barrels per day over 30 days. The scenarios submitted by Shell Oil showed that most of this 165,000-barrel volume could be contained and recovered. Missing from Shell's oil spill contingency plan for the U.S. Arctic Ocean, and from the MMS (now BOEMRE) review of spill planning capacity, is a realistic estimate of how Arctic conditions might limit spill response operations.

This section highlights areas where U.S. oversight of oil spill response planning in the Arctic OCS may not be taking into account the realistic limits to containing and cleaning up an oil spill. The concept of an oil spill response gap is introduced, and the need for additional response gap analysis is explained. A review of oil spill planning assumptions and oil spill response capacity in the U.S. Arctic Ocean is presented to demonstrate that additional planning and preparedness are necessary to minimize the potential for a catastrophic blowout while also ensuring that if a major spill should occur, it would be contained and cleaned up as quickly and effectively as possible.

6.1 Arctic Oil Spill Response Gap

A response gap exists whenever environmental conditions exceed the operating limits of oil spill cleanup equipment, meaning that if a spill occurred during this time, it could not be contained or cleaned up (Nuka Research 2006 and 2008). The term "response gap" is relatively new to the published literature, and there has been some confusion about what the term means and how it relates to other oil spill planning and response concepts.

A response gap estimate, which is typically expressed as a percentage, has nothing to do with the percentage of oil that could be recovered. It is an estimate of how frequently conditions on the scene would exceed the limits of all available technologies to safely and effectively operate, meaning that during those times, either no spill response would be attempted, or attempts to

(Photo credit: U.S. Coast Guard response boat. *Kurt Fredrickson/USCG*) recover oil would be unsuccessful. When a response gap exists 65 percent of the time at a given oil spill location, it means that on 65 out of 100 days, no response would be conducted and no oil would be recovered, for reasons that may vary from logistical to practical to safety. Recovery percentages and response effectiveness would come into play during the other 35 days, when it would be possible to send out oil spill response equipment. Although it has not been described as such, a response gap occurred several times during the Deepwater Horizon response, when high winds and storm conditions prompted managers to cease on-water operations for a period of hours or days.

6.1.1 Response Limit Estimates for U.S. Arctic Ocean

In considering the response gap for the U.S. Arctic Ocean, it is necessary first to identify the upper limits of the response systems in place. A response gap exists during periods when at least one of these upper limits is realized. Upper limits may include ice conditions, visibility, wind, sea state, temperature or other physical or environmental parameters. (Table 5-1 summarizes how each of these parameters limits oil spill response.) The upper limits of a spill response system involve a dynamic interplay among multiple factors and the individual components of a response system. However, once the upper limit is reached for one component of a system, it has been reached for the system.

Establishing response limits for oil spills in the Arctic Ocean is a challenge, especially given the limited data available from actual spills in Arctic waters. The degradation of spill response capability does not occur at a single point, nor is it necessarily linear in nature. For instance, if 30 percent ice coverage is considered to be the operating limit for mechanical recovery, this does not mean that mechanical response efficiency would plummet to zero as ice coverage increases from 29 percent to 30 percent. Likewise, ice coverage of 15 percent does not indicate that the response efficiency is twice as high as it would be at 30 percent. The degradation curve is probably different for each environmental factor that affects spill response. This further complicates the task of setting discrete operational limits for any one factor.

In considering operating limits for the Arctic Ocean, it is also important to recognize that these limits are just as likely to be realized because of limits to the vessels or aircraft required to carry out the response as they are because of limits to the spill recovery or treatment technology. If helicopters or vessels cannot access an area to initiate in-situ burning because of ice conditions or visibility limits, then the response is not feasible, even if experiments have shown that oil can be ignited under similar conditions.

In addition to ice coverage, the type of ice has a documented impact on spill response limits. Each of the different ice regimes (solid ice, open water, fall freeze-up, spring breakup) will limit the safety, effectiveness or operational feasibility of oil spill response systems. During the transitional ice seasons in the U.S. Arctic Ocean (freeze-up and breakup), ice conditions are so dynamic that a technique that may be appropriate for use one day could be useless the next (Evers *et al.* 2006).

During times when ice conditions may be favorable for response, other conditions, such as wind and waves, may create a response gap. For example, the "Field Guide for Oil Spill Response in Arctic

Waters" recommends that wind speeds above 30 mph and wave heights above six feet be the maximum operating limit for in-situ burning and mechanical recovery (Owens *et al.* 1998). Waves that are considerably smaller than six feet in height may limit response if the wave period (distance and time between waves) is short.

Rules of thumb have been developed to estimate whether oil spill response techniques or equipment may be used under a range of ice conditions. It is important to recognize that these are theoretical estimates only; little real-world data are available to corroborate these figures. Several published sources estimate the operating limits to oil spill response techniques posed by ice coverage, wind, waves and visibility (Owens *et al.* 1998, Fingas 2004, Evers *et al.* 2006, Robertson and DeCola 2001).

The response gap for oil spill response in the U.S. Arctic could be quantified by comparing historical climatic data against a set of upper limit parameters, such as those listed in Table 6-1.

Table 6-1. Matrix of Approximate Oil Spill Response Limits—This matrix summarizes the generally accepted response limits to mechanical recovery (with and without ice management) and in-situ burning as they correlate to a range of ice coverage, wind, wave height and visibility conditions. Green blocks indicate conditions generally considered to be favorable for the response technique. Yellow blocks indicate that conditions may impede response operations. Red blocks indicate that response would not be possible under these conditions. Note that any single "red" factor could shut down a response. Similarly, a combination of yellow factors may have an aggregate impact on response. More work is needed to understand these limits and their impact on oil spill response capability in the U.S. Arctic Ocean. "Green" indicates only that the technique may be feasible; the effectiveness of that technique in removing or treating oil may still be limited. Dispersants are not included in this table because they are not a mature technology and have not been pre-authorized for use in the U.S. Arctic Ocean.

LIMITING FACTOR	ICE COVERAGE					WIND			WAVE HEIGHT			VISIBILITY		
Conditions	<10%	11% to 30%	31% to 70%	>70%	Solid Ice	0-20 mph	21-35 mph	>35 mph	<3 ft	3-6 ft	>6ft	High	Moderate*	Low*
Mechanical recovery with no ice management	Yellow	Red	Red	Red	Green	Green	Yellow	Red	Green	Yellow	Red	Green	Yellow	Red
Mechanical recovery with ice management	Green	Yellow	Red	Red	n/a	Green	Yellow	Red	Green	Yellow	Red	Green	Yellow	Red
In-situ burning	Yellow	Green	Green	Yellow	Green	Green	Red	Red	Green	Yellow	Red	Green	Yellow	Red

*Moderate visibility = light fog or <1 mile visibility; low visibility = heavy fog, <¼ mile visibility, or darkness

Response limits may also be driven by a combination of factors that individually would not affect the response. The cumulative effect of two or more environmental factors is not necessarily equal to the sum of the two factors individually, and the interaction of the factors could cause more extreme impacts. For example, the combination of wind and cold can cause the wind chill factor to make air temperatures dangerous to responders, or cause ice to form on vessels and equipment, making them unsafe or unstable (Figure 6-1). The combination of sea ice and low visibility might make vessel operations too dangerous. Waves of a certain height or period present a greater obstacle to response operations when there is a strong wind or low visibility.

Figure 6-1. Ice can form on vessels, making it more difficult to operate machinery and equipment *(Photo Credit: USCG).*

Table 6-2 provides a general seasonal listing of environmental factors that can affect and limit response operations in the U.S. Arctic, resulting in response gaps. The data are limited and based on climatological history for the communities of Barrow and Wainwright. Weather parameters may differ at the actual location of an incident. Information associated with sea state and wave height is not available because of the lack of weather buoys in the U.S. Arctic region.

Table 6-2. Environmental Factors Affecting Operational Limitations in the U.S. Arctic Ocean *(adapted from data at Western Regional Climate Center 2009a & 2009b).*

Environmental Factors and Response Gaps (Estimated Percentage of Time When Operating Limits Are Impaired or Exceeded in U.S. Arctic)			
Winter (Jan-March)	**Spring (April-June)**	**Summer (July-Sept)**	**Fall (Oct-Dec)**
Ice Condition: Solid (100%) Approx. Daylight Hrs 4.5 Avg. # Days Peak Gust >30: 20 (22%) Avg. # Days of Fog: 51 (57%) Avg. Ext Min Temp: -49F	Ice Condition: Solid (80%), Broken Ice (20%) Approx. Daylight Hrs 19 Avg. # Days Peak Gust >30: 12 (1%) Avg. # Days of Fog: 53 (58%) Avg. Ext Min Temp: -9F	Ice Condition: Broken Ice (60%) Open Water (40%) Approx. Daylight Hrs 21 Avg. # Days Peak Gust >30: 19 (21%) Avg. # Days of Fog: 44 (49%) Avg. Ext Min Temp: 20F	Ice Condition: Open Water (20%), Broken Ice (60%), Solid (20%) Approx. Daylight Hrs- 5.5 Avg. # Days Peak Gust >30: 30 (34%) Avg. # Days of Fog: 51 (57%) Avg. Ext Min Temp: -32F

6.2 Gaps in Oil Spill Response Planning for the U.S. Arctic Ocean

Plans to drill exploratory wells up to 200 miles offshore in the Chukchi Sea would have created the potential for a subsea well blowout in an area of the U.S. Arctic Ocean where there is no ongoing oil exploration or production, and where the capacity to clean up an oil spill in the presence of seasonal sea ice is unproved.

6.2.1 Oil Spill Contingency Planning for Chukchi Sea Leases

Under existing U.S. regulations, once an offshore lease sale is completed, the lessees begin the process of developing an exploration oil discharge prevention and contingency plan[1] (ODPCP or "C-plan"), which is an important link between operational risks and response capabilities. The plan describes how available resources would be applied to a release of oil under a range of potential circumstances. A C-plan for OCS exploration and production operations is required under 30 CFR Part 254 and must be submitted to the BOEMRE (formerly MMS) for review and approval.

A lessee's C-plan must include a worst-case discharge scenario. Section 311 of the Clean Water Act (33 USC § 1321 (a)(24)) defines "worst-case discharge" as "the largest foreseeable discharge in adverse weather conditions."[2] Under the MMS regulations (30 CFR 254.47(b)), an operator's worst-case discharge scenario is the daily volume possible from an uncontrolled blowout. In determining the daily discharge rate, the operator must consider any known reservoir characteristics. If reservoir characteristics are unknown, the operator must consider the characteristics of any analog reservoirs from the area and give an explanation for the selection of the reservoir(s) used. The scenario must discuss how to respond to a well flowing for 30 days (30 CFR 254.26(d)(1)). The adverse weather conditions that must be addressed include, but are not limited to, fog, inhospitable water and air temperatures, wind, sea ice, current and sea states (30 CFR 254.6). It

1 Also referred to as a response plan.

2 Adverse weather conditions are conditions found in the operating area that make it difficult for response equipment and personnel to clean up or remove spilled oil or hazardous substances (30 CFR 254.6).

does not refer to conditions such as a hurricane, under which it would be dangerous or impossible to respond to a spill (30 CFR 254.6).

Shell, the largest leaseholder in the Chukchi Sea, submitted exploration plans and a C-plan to the MMS, and these plans were approved in December 2009 and finalized in March 2010 (Shell 2010). The Shell C-plan includes blowout scenarios, but the scenarios presented do not reflect a true worst-case discharge or response. They fall short of the regulatory requirement to plan for a "worst case discharge under adverse conditions" and thus do not provide any real assurance, should a major well blowout occur from drilling in the offshore Arctic.

6.2.2 Planning Assumptions in Shell's Chukchi Sea Oil Spill Contingency Plan

FLOW RATE FOR BLOWOUT

Shell's C-plan is based on the Alaska Department of Environmental Conservation (ADEC) well blowout response planning standard of 5,500 barrels per day, multiplied by the federal response planning period of 30 days. Uncontrolled well flow may be significantly higher, because other North Slope wells have had production rates in excess of 10,000 barrels per day when first drilled.

SPILL RECOVERY ESTIMATES

Shell includes a planning assumption that 90 percent of the oil discharged from a blowout would be contained and recovered by the primary offshore response task forces, and that only 10 percent would escape and drift toward shore. Shell expects that half the oil reaching the nearshore environment would be recovered by additional skimming systems deployed from a response barge using a tactic similar to the one that was tested during the 2000 broken-ice exercises and shown to be limited to very low ice concentrations. The C-plan does not explain how Shell arrived at the assumption that 90 percent of the oil would be contained and recovered from the sea surface. By comparison, only 3 percent of the estimated 4.9 million barrels of oil spilled during the Deepwater Horizon incident was recovered by offshore containment and skimming operations.

Recovery of such a large amount of oil, though unrealistic as a planning assumption, would create a storage crisis, based on the resources Shell has identified in its plan. Shell lists a total of 545,246 barrels of on-water storage capacity for recovered oil and water. With a blowout scenario of 5,500 barrels per day, assuming that the oil is recovered as an emulsified oil/water mixture, Shell would fill this available storage on day 13 of the blowout. If Shell were permitted to decant the oil/water mixture (separate the oil from the water and discharge the water), then the storage could last 30 to 45 days.

SOURCE CONTROL

The Shell C-plan is predicated on a number of assumptions. One of the most problematic assumptions is that the Frontier Discoverer, the drill ship that would drill the exploratory wells, would be able to drill its own relief well if a subsea blowout should occur. This requires that the drill ship be undamaged by a well blowout, which is highly unlikely. The two most recent well blowouts—the Montara platform blowout in the Timor Sea and the Deepwater Horizon blowout in the Gulf of Mexico—involved explosions and fires that damaged the drilling structure. Fire and explosion are not uncommon for well blowouts, because the materials that are released typically include flammable gases. (See list of well blowouts, Table 3-2.) Even if a fire or explosion did not occur, ignition of flammable gases is always a concern.

A blowout typically results in evacuation of personnel from the drill ship, which would make starting and moving the ship extremely difficult. A review of all available data about well blowouts worldwide does not show a single example of a drill ship drilling its own relief well after blowing out. Thus the Shell strategy is without precedent. During the 1980s, the original exploration plans for the Chukchi Sea also called for the drill ship to drill its own relief well in the event of a blowout, but before drilling commenced, the operators were required to arrange for a second drill ship to be on standby in the Canadian Arctic in case the first rig was damaged or unable to complete the relief well (Hinkel *et al.* 1988).

Shell justifies the drill ship/relief well plan on the basis that several layers of protection are in place to prevent a blowout from occurring, and the assumption that the blowout would never be severe enough to prevent the drill ship from drilling another well. The Deepwater Horizon provided an example of how protective barriers can fail.

Given the fact that the C-plan is questionable, the 30-day time frame for controlling the well may also be overly optimistic. The relief well plan included in the C-plan even acknowledges that it could take 34 days to drill a relief well to 14,000 feet true vertical depth. Shell does not consider the possibility that more than one attempt may be required to drill a successful relief well. The Montara blowout took more than 70 days to control, in part because the first four attempts to drill a relief well were unsuccessful.

Shell's worst-case discharge scenario assumes that a well blowout would occur early in the drilling season, allowing enough time to drill a relief well and control the blowout before fall freeze-up (October or November) begins to encroach on the drill site. A spill that occurred later in the drilling season might not allow enough time to drill a relief well before sea ice conditions make it unsafe to continue drilling. Under such a scenario, the well would continue to blow out through the winter ice season until well control could be attempted after the spring thaw in May or June.

WEATHER CONDITIONS

Shell's C-plan contains a scenario that presumes that the weather, temperature and sea state remain consistent throughout the 30-day response period and have no negative impacts on response capability and capacity. This is an unrealistic assumption. Even during the Deepwater Horizon response, weather and sea state caused response operations to be curtailed several times. In the offshore Chukchi Sea, the combination of wind, waves and dynamic sea ice can severely hamper or even preclude oil spill cleanup (Table 6-1).

Shell states in its C-plan that the well drilling activities would not be conducted after Oct. 31. Typically, the Chukchi Sea is ice-free in mid-September. By early September, the ice edge is at its northernmost point. During the last week of September, new ice typically begins to form within the marginal ice zone. As the temperatures begin to decrease, new ice continues to thicken, and the ice edge gradually moves southward. By the second week of October, new ice growth is well underway. The Arctic pack ice will be drifting southwest with concentrations of multiyear ice at more than seven-tenths, with the remainder being young ice. As the amount of sunlight rapidly declines, temperatures decrease in mid-October, and rapid refreezing of leads and any other openings in the ice is expected. Ice will also begin to grow along the Alaskan coast during the first week of October, with fast ice forming along the Barrow coast by the third week of October.

The average wind speed in mid-September through November for Wainwright, Alaska, is approximately 12 mph, with daily gusts averaging 23 mph. The average wind speed and daily gust average for Barrow, Alaska, are similar. Sea state data is less reliable, but seas of 10 to 20 feet are not uncommon. The plan does not address visibility limits for on-water and aerial surveillance and support activities. Fog is persistent throughout the area, with an average number of 21 foggy days per month. Heavy fog with a visibility less than or equal to one-quarter mile occurs an average of three days per month during this time frame. Fog would make on-water and aerial response activities unsafe or unfeasible.

The Shell C-plan does acknowledge the possibility that oil spilled late in the drilling season could become encapsulated in fall freeze-up or trapped under ice floes through the winter. The spill plan presents this as a favorable condition, assuming that any oil trapped over the winter would remain in place and be just as easy to remove or treat after eight months in the sea ice. Sea ice is dynamic and constantly moving, however, and oil trapped under or within ice could be extremely hard to even locate in the springtime. Oil trapped under multiyear ice could remain in the marine environment for many years. A scenario developed in the mid-1980s for the Chukchi Sea estimated that spilled oil trapped in ice could move as much as 300 to 500 miles (Lewbell and Galloway, 1984 in NRC 2003b).

The period from August until freeze-up is typically the most active storm season in the offshore Chukchi, with severe storms resulting in high winds and sea states, freezing spray and coastal erosion. An oil spill plan would take into consideration historical weather patterns and plan for the possibility that conditions may not be ideal. Federal regulations specifically require that worst-case oil spill scenarios address "adverse weather conditions," but the Shell plan, approved by the MMS, certainly does not address adverse weather (30 CFR 254.26(d)).

6.2.3 Gaps in Response Capacity for Subsea Well Blowout in the Chukchi Sea

Based on the major response activities described in the Shell scenario and the resource requirements to meet the response commitments made in the C-plan, there appear to be major gaps in the capacity of existing response equipment and technologies to respond to a blowout from a subsea well in the Chukchi Sea or elsewhere in the U.S. Arctic Ocean.[3]

One major gap apparent in the Shell Chukchi C-plan is that in many cases, spill response operations depend upon the same pieces of equipment or vessels to support multiple functions simultaneously. Another problem is a lack of consideration for the logistical challenges of

3 This analysis takes into consideration only mechanical recovery operations, not the use of chemical dispersants or in-situ burning Although Shell's Chukchi leases are in federal waters, the C-plan conforms to State of Alaska requirements that planholders demonstrate that they can meet their oil spill cleanup requirements solely through mechanical recovery. The State of Alaska prioritizes mechanical recovery over dispersant use and in-situ burning.

mounting a major spill response offshore in a region with limited coastal infrastructure. The Shell C-plan indicates that the primary incident command post would be in Anchorage, Alaska (see Figure 2-13). The plan does not identify the number of industry, contractor and agency personnel needed to sustain the response. Logistical support and staging areas would also need to be established in Barrow, Wainwright, Point Lay or Point Hope, the only coastal communities with sufficient airstrips.

In an attempt to demonstrate some of the shortfalls in the level of contingency planning accepted for Arctic Ocean oil spills, the major response activities in the Shell C-plan and the response limitations are considered, based on the discussion in Section 6.1.

Table 6-3 (at the end of this section) summarizes the resource requirements, task force, function, response tactics, minimum required response resources, and source of resources listed in the Shell C-plan. The resources summarized are for surveillance and tracking, offshore recovery, transfer and storage of recovered oil, nearshore recovery, and sensitive area protection.

Alaska Clean Seas (ACS) is the primary oil spill response contractor for the U.S. Arctic region. The Alaska Clean Seas Equipment Manual provides a guide to the location, ownership, type, amount and specifications of most of the North Slope response equipment (ACS 2009). Although ACS has a significant equipment stockpile to support operations in shallower, nearshore waters, it has limited offshore capabilities.

SURVEILLANCE AND TRACKING

The Shell Chukchi Sea contingency plan does not clearly identify the resources that would be used to carry out the aerial surveillance of oil on the water. Two helicopters are identified in the C-plan. It is assumed that the Twin Otter aircraft with forward-looking infrared radar (FLIR) from Kuparuk would be used initially and based in Barrow for this response, but FLIR technology is limited by ice conditions (it cannot be used under fast ice). It is also affected by cloud cover and fog and can be used only during daylight. This resource can be obtained through the mutual aid contract with North Slope Operators and Alaska Clean Seas. As with all offshore oil spill response operations, other commercial aircraft and helicopters would need to be contracted to conduct aerial surveillance and tracking of the oil and to support the operation. (More than 100 fixed-wing aircraft and helicopters were used during the Deepwater Horizon oil spill response.) An impediment to aerial surveillance during this time frame is the presence of fog or ice. As noted, the monthly average of foggy days in the region is 21 during the ice-free season.

In the Shell C-plan, spill tracking buoys will also be deployed to assist in determining where the oil is being transported and at what rate. In addition to the hand-held tracking buoys, Shell plans to track the discharge using satellite technology. When cloud-free, visible imagery is an excellent source. However, because the Arctic has few days that are cloud free, high-resolution all-weather imagery will be necessary for consistent operational support. As freeze-up sets in, tracking and monitoring the movement of oil will be increasingly difficult, and innovative options or commercially available technology will need to be used. Shell's contingency plan suggests the possible use of the Shell Global Source Light Touch System (gas detector), ground-penetrating radar and laser fluorosensors. Although commercially available, all of these technologies are experimental when applied to tracking oil that is under or mixed in the ice.

OFFSHORE RECOVERY

Shell's offshore recovery revolves around four primary response vessels and eight workboats that would be on site for the drilling period and other response resources located hundreds of miles from the drill site. MMS never required Shell to demonstrate, beyond its descriptions in the C-plan, whether this equipment was sufficient to clean up a worst-case oil spill far offshore that lasts 30 days or longer. The immediate availability and significant amount of spill response equipment in the Gulf of Mexico after the Deepwater Horizon blowout demonstrates that when a catastrophic spill occurs, no amount of equipment is enough. The limited personnel and vessels and few thousand feet of ocean boom that Shell plans for its offshore spill response would be insufficient for cleaning up a major spill in the remote Chukchi Sea. Alaska Clean Seas has limited equipment suitable for offshore operations. MMS did not require any testing or exercises to explore the limits of existing spill cleanup equipment for offshore response when sea ice is present.

NEARSHORE RECOVERY AND PROTECTION OF SENSITIVE RESOURCES

The Shell C-plan shows that three task forces are assigned to nearshore recovery to apply five different response tactics. Shell intends to deploy protective boom at seven priority protection areas (PPA) identified in the scenario along Chukchi Sea shoreline areas. Table 6-3 summarizes the resource requirements for boom, workboats and personnel to deploy all of these strategies when they arrive on Day 5. As these activities are going on simultaneously with offshore recovery and nearshore recovery, the resources required to deploy sensitive area protection tactics are presumed to be dedicated to sensitive areas and are not available to other task forces. The resources listed in the Shell C-plan are:

- Amount of boom required to implement all priority protection strategies is 6,200 feet.
- Fourteen workboats and 44 trained responders/vessel operators to deploy and seven workboats and 21 trained responders/vessel operators to tend and maintain boom.
- Mobilization plan for vessels, personnel and boom is unclear from the scenario. ACS provides all equipment, vessels and personnel.
- ACS vessels and personnel would probably require transportation via vessel or barge to get from Prudhoe Bay to the protection sites. Some sites have significant draft restrictions.

The Shell C-plan clearly indicates that the shoreline protection will be sharing resources and personnel, which will create a conflict of resource priorities.

SHORELINE IMPACT

Shell's C-plan discounts the potential for shoreline impacts, noting that it is "highly unlikely that oil could impact the nearshore environment in less than six days." The C-plan goes on to state that "even if oil did survive that long in the open ocean, there would be ample time to monitor its movement, prepare to intercept and recover it, and to position shoreline protection and cleanup crews at priority protection sites well before the oil may arrive." This statement seems to all but dismiss the potential for a spill from the exploration operations to affect shoreline areas, even though the closest drill site is about 60 miles from the shoreline.

A large oil spill would undoubtedly have shoreline impacts, as we have seen time and again in major oil spills. The Exxon Valdez oil spill migrated 460 miles and affected more than 1,300 miles of noncontiguous shoreline. The Deepwater Horizon spill has affected coastlines in four Gulf Coast states. Little is known about currents and wind direction in the U.S. Arctic Ocean, so it is virtually impossible to know in what direction the oil will go. During the first week of October, ice will begin to form along the shoreline, and oil would probably become encapsulated in ice, making access to sites and any shoreline cleanup activities challenging.

CASCADING OF ADDITIONAL OIL SPILL RESPONSE RESOURCES

Shell's C-plan indicates that if additional response resources were needed to adequately clean up an oil spill, the company would activate existing contracts with the Marine Spill Response Corporation, Oil Spill Response in Southampton, United Kingdom, and the mutual aid agreements through Alaska Clean Seas. Personnel and equipment would join the response from other locations in Alaska and worldwide. Shell's C-plan does not explain how these additional resources would be mobilized from the various airports (Barrow, Point Hope, Wainwright) to the spill location. The infrastructure and road system in the smaller communities are limited and cannot support a Deepwater Horizon size response.

Accessing the North Slope communities by vessel also presents a challenge and is weather dependent. The entrance to Wainwright Inlet is a narrow, winding channel. Its depth is approximately six feet, enough to accommodate shallow-draft barge traffic, but passage should not be attempted without the aid of local guides and/or pilots during open-water season. Shoals extend approximately seven-tenths of a mile off the inlet and are well defined by breakers during moderate weather. During west storms, the breakers stretch across the channel. Point Hope is located on the Chukchi Sea with a nearshore current of 1 knot, increasing to 2 to 3 knots near Point Barrow. Barrow can be accessed by vessel during open-water season, but there is no protection from heavy weather.

Table 6-3. Resource Requirements and Operating Limitations.

Shell Task Force Purpose and Name	Minimum Required Response Resources[1]	Potential Shortfalls or Operating Limitations	ENVIRONMENTAL FACTORS AND OPERATING LIMITATIONS			
			Winter (Jan-March)	Spring (April-June)	Summer (July-Sept)	Fall (Oct-Dec)
Surveillance and Tracking (No task force number assigned in C-plan)	1 Kuparuk Twin Otter aircraft with FLIR Spill tracking buoy system 1 workboat (deploy tracking buoys) 6 trained personnel per shift Satellite tracking	Resources not clearly identified in Shell scenario. No contract found in Shell C-Plan for this service.	Primary limitation for aerial operations will be associated with visibility (57%). Day visual flight rule (VFR) only for field ops. Whiteout, blizzard conditions, limited daylight hours and ice fog.	Limitations: Visibility associated with fog, ice fog (58%) icing on aircraft, day VFR operations only for field ops.	Limitations: Visibility associated with fog (49%), day VFR operations only for field ops.	Limitations: Visibility associated with whiteouts, fog, ice fog (57%) icing on aircraft, day VFR operations only for field ops.
Offshore Recovery [2] TF-1	1 OSRV w/ 12,000 bbl storage 1 Transrec 150 Skimmer 1 OSRV supervisor 1 OSRV operator 3 34-ft workboat operators (shared with TF-2) 3 34-ft workboat crew 7 OSRV deck crew 1 100-bbl bladder	Three 34-ft workboats, operators and crew are shared with TF-2.	Solid ice precludes on-water vessel operations.	Limitations for offshore oil recovery include: Visibility-whiteout, blizzard conditions, ice fog and extreme temperatures (58%). May-June breakup will preclude use of vessels nearshore. Solid ice present offshore precludes vessel operations.	Limitations: Broken ice conditions and open water. Ice management needed in broken ice areas for effective response. Open water affected by wind speeds and gusts >30 kts (21%), visibility due to fog (49%).	Limitations: Open water and broken ice. Ice management needed in broken ice areas for effective response. Open water affected by wind speeds and gusts >30 kts (34%), visibility due to fog (57%). Extreme temperatures would cause icing on vessels and response recovery equipment.
Offshore Recovery TF-2 (24 hr)	1 Transrec 150 skimmer 1 Vessel of Opportunity Skimming System (VOSS) w/ 3,200 bbl storage 1 VOSS supervisor 2 VOSS deck crew 3 34-ft workboat operator (shared with TF-1) 3 34-ft workboat crew	Beginning Day 2, the TF team leader/ field supervisor is accounted for in TF-1.	Solid ice precludes on-water vessel operations.	Limitations for offshore oil recovery include: Visibility-whiteout, blizzard conditions, ice fog and extreme temperatures (58%). May-June breakup will preclude use of vessels nearshore. Solid ice present offshore precludes vessel operations.	Limitations: Broken ice conditions and open water. Ice management needed in broken ice areas for effective response. Open water affected by wind speeds and gusts >30 kts (21%), visibility due to fog (49%).	Limitations: Open water and broken ice. Ice management needed in broken ice areas for effective response. Open water affected by wind speeds & gusts >30 kts (34%), visibility due to fog (57%). Extreme temperatures would cause icing on vessels and response recovery equipment.

Shell Task Force Purpose and Name	Minimum Required Response Resources[1]	Potential Shortfalls or Operating Limitations	ENVIRONMENTAL FACTORS AND OPERATING LIMITATIONS			
			Winter (Jan-March)	Spring (April-June)	Summer (July-Sept)	Fall (Oct-Dec)
Transfer & Storage of Recovered Oil TF-3	1 Oil Spill Tanker (OST) 1 Tanker Deck Person-in-Charge (PIC) 1 Tanker operator 3 Tanker deck crew (1 per shift)	Crude oil capacity = 513,000 bbl. All TF-3 tasks including PIC will be performed by tanker crew with no additional response staff from Shell or ACS.	Solid ice precludes on-water vessel operations.	Solid ice and spring breakup conditions near retreating ice edge would preclude the OST to be in the area until July.	Open water affected by wind speeds and gusts >30 kts (21%), visibility due to fog (49%).	Open water affected by wind speeds and gusts >30 kts (34%), visibility due to fog (57%). Extreme temperatures would cause icing on vessels and response recovery equipment. OST would need to depart region prior to freeze-up.
Nearshore & Shoreline Recovery TF-5 (96 hr)	1 OSRB/tug w 16,000 bbl capacity 1 OSRB supervisor 1 nearshore recovery supervisor 4 Lamor LSC-5 skimmers (2 per vessel) 1 47-ft skimmer boat 1 47-ft skimmer boat operator 2 47-ft skimmer boat crew 3 34-ft workboats 3 34-ft workboat operator 3 34-ft workboat crew 4 249-bbl storage 200 m boom 6,000-ft coastal boom		Solid ice precludes on-water vessel operations.	Solid ice and spring breakup conditions near retreating ice edge would preclude the OSRB to be in the area until July.	Limitations: Broken ice conditions and open water. Ice management needed in broken ice areas for effective response. Open water affected by wind speeds and gusts >30 kts (21%), visibility due to fog (49%)	Limitations: Open water and broken ice. Ice management needed in broken ice areas for effective response. Open water affected by wind speeds and gusts >30 kts (34%), visibility due to fog (57%). Extreme temperatures would cause icing on vessels and response recovery equipment.

Shell Task Force Purpose and Name	Minimum Required Response Resources[1]	Potential Shortfalls or Operating Limitations	ENVIRONMENTAL FACTORS AND OPERATING LIMITATIONS			
			Winter (Jan-March)	Spring (April-June)	Summer (July-Sept)	Fall (Oct-Dec)
Nearshore & Shoreline Recovery TF-6 (96 hr)	4 workboats 18-22 ft plus 4 operators and 4 crew 2 workboats 29 ft plus 2 operators and 2 crew 2 24-ft workboats plus 2 operators and 2 crew 2 landing craft plus 2 operators and 2 crew 18,000-ft boom 8 shoreline protection laborers	Boats and landing craft are shared by TF-6 and TF-7. TF-5, TF-6 and TF-7 operate one 12-hour shift per day.	Solid ice precludes on-water vessel operations.	Solid ice and spring breakup conditions near retreating ice edge would preclude the OSRB to be in the area until July.	Limitations: Broken ice conditions and open water. Ice management needed in broken ice areas for effective response. Open water affected by wind speeds and gusts >30 kts (21%), visibility due to fog (49%).	Limitations: Open water and broken ice. Ice management needed in broken ice areas for effective response. Open water affected by wind speeds and gusts >30 kts (34%), visibility due to fog (57%). Extreme temperatures would cause icing on vessels and response recovery equipment.
Nearshore & Shoreline Recovery TF-7	See TF-6 resources 20 oleophilic skimmers 36 bladders (500 to 2,640 gal.) 50 portable folding tanks (2,500 gal.) 8 shoreline recovery laborers	Trained shoreline assessment teams (minimum of 4 personnel per team with requisite training). Helicopter for transportation.	Solid ice precludes on-water vessel operations.	Solid ice and spring breakup conditions near retreating ice edge and shoreline would restrict access to beaches needing cleanup.	Visibility limitations due to fog (49%) to support shoreline cleanup crews via vessel and helicopter.	Freeze-up and solid ice conditions affect access to shoreline due to ice. Wind speeds and gusts >30 kts (34%), visibility due to fog (57%). Extreme temperatures would cause icing of recovery equipment. Aerial operations limitations: icing on aircraft, day VFR operations only for field ops (5.5-0 hours).

1 Per task force, with the exception of sensitive area protection, which shows the requirements for deployment of all priority protection sites simultaneously. Sequential deployment of sensitive area protection resources will reduce the number of workboats and personnel required but will not affect the total amount of boom.
2 Table 1.6-5 Shell Contingency Plan lists two skimming alternatives to be considered for use by TF-1 but only one option would be used in the scenario.
3 Note: This table contains no TF-4 "Non-mechanical response." TF-4 includes designation of both a C-130 aircraft (based in Arizona) with integrated dispersant tank and spray arms and the chemical dispersant Corexit 9500. This table addresses mechanical recovery options that are primarily in-state and readily available.

6.2.4 Gaps in Planning and Response Capacity in the Beaufort Sea

Sections 6.2.1 through 6.2.3 of this report discuss the gaps in planning and preparedness for oil exploration in federal waters up to 200 miles offshore in the Chukchi Sea. Many of the same challenges described for the Chukchi Sea would carry over to exploratory drilling in areas of the Beaufort Sea. A more detailed analysis of the extent and nature of the response gap in both the Chukchi and Beaufort seas is warranted and should address the similarities and differences between the two operating environments.

Most of the limiting factors discussed in the context of the U.S. Arctic Ocean—such as high winds, severe storms, heavy seas, low visibility, cold temperatures and seasonal ice—apply to both the Beaufort and Chukchi seas. However, there are differences between the two operating areas that may alter the challenges.

WATER DEPTHS AND DISTANCE FROM SHORELINE

Existing production operations in state and federal waters of the Beaufort Sea are clustered in shallower areas within a few miles of the shoreline (Figure 3-3). Thus far, these operations have been conducted from man-made gravel islands at water depths below 80 feet. Expanded drilling or production in deeper waters farther from shore may require floating or bottom-founded structures, as discussed in Chapter 3. For now, drilling operations that are conducted from islands closer to shore have both advantages and disadvantages from a spill planning perspective. Oil spills from exploration and production operations closer to shore will have more rapid shoreline impacts. However, blowouts from island drilling structures may be easier to control because the blowout preventers are located at the surface rather than underwater. That factor, combined with seasonal drilling restrictions, gives responders a better chance of cleaning up oil spilled on top of solid ice.

SEASONAL DRILLING

Exploratory drilling in the Beaufort Sea has been conducted during the winter season, when the nearshore Beaufort is frozen solid and spill response tactics would involve operating vehicles and equipment from the solid land-fast ice coverage. Spills on top of solid ice present their own challenges but are typically easier to clean up than spills in open water or broken ice during the freeze-up, breakup or open-water seasons. Because production operations continue year-round in the Beaufort Sea, the potential for a spill during freeze-up or breakup exists, and such a spill may be even more challenging because of the operating conditions there. The shallow nearshore Beaufort is not deep enough for ice-class vessels to operate; therefore, the small workboats that would form the basis of the response would be limited to operating in areas of lower ice concentration. The open-water season in the Beaufort Sea is about a month shorter than in the Chukchi Sea, further limiting the response window for on-water cleanup.

WORST-CASE BLOWOUT VOLUMES

Although data are limited on well-bore pressure and potential blowout rates in the Chukchi Sea, more information is available about the potential blowout rates for Beaufort Sea wells. The contingency plan for the Liberty development project in the Beaufort Sea has the highest flow rates in the U.S. Arctic and a potential open-orifice blowout of 20,000 barrels a day. A blowout from a Beaufort Sea well that occurs during the end of the brief open-water season could continue uncontrolled over the nine-month ice season and result in a spill larger than the Deepwater Horizon blowout that is trapped within and among sea ice until the spring melt.

RECOMMENDATIONS 7

A great deal of work is required to guide responsible management and ensure that the best decisions are made to prevent and respond to oil spills in the Arctic Ocean. Significant gaps exist in knowledge, planning, and oversight in the areas of oil spill risks, impacts and response capabilities, and these gaps must be closed before the United States moves forward with oil exploration and production activities in the Arctic OCS.

The following recommendations are presented based on the analysis in this report, with the goal that implementation of some or all of these initiatives will lead to responsible management of the Arctic OCS and prevent oil spills from adversely affecting the environment, ecology and indigenous people who rely on a healthy and pristine Arctic Ocean.

The recommendations offered here relate to the key concepts explored in this report:

- The Arctic Ocean is different from any other area of the U.S. OCS.
- Government and industry oil spill plans underestimate blowout risks in the Arctic Ocean.
- An oil spill could devastate the Arctic ecosystem.
- Oil spill response systems are unproved during most of the year in the U.S. Arctic Ocean.
- An Arctic Ocean oil spill response gap exists.

7.1 Improve Arctic Oil Spill Science, Monitoring and Assessment

The "Guidelines for Arctic Oil and Gas Development," published by the Arctic Council in 2009, cautions:

> *"Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."*

Baseline science for Arctic marine environments is improving but is still very limited. Research is ongoing by the U.S. Geological Survey (USGS) to identify major gaps in Arctic science. Such work is critical to develop a comprehensive, collaborative program of research, monitoring, data collection, mapping, and documentation of local and traditional knowledge in the U.S.

(Photo credit: *Patrick Kelley, USGS)*

Arctic. Arctic ecological science, monitoring and assessment should be integrated with oil spill prevention and response planning.

At work in the Arctic is a complex interplay of environmental conditions, climate, wildlife population dynamics and human activity. The prospect of conducting baseline studies to better delineate environmental and wildlife sensitivities, while increasing our scientific knowledge base regarding the Arctic ecology and sensitivity to oil spills, is daunting. Yet such research is critical and must be initiated before the introduction of new oil spill risks.

7.1.1 Close the Knowledge Gaps Regarding Arctic Oil Spill Impacts

Additional research is needed to better understand the fate and impact of oil spilled in a seasonal ice environment and to explore the short- and long-term toxicity of spilled oil to the Arctic ecosystem and food webs.

A 2007 assessment of worldwide oil exploration and production activities in Arctic regions emphasizes that the current state of knowledge regarding Arctic oil spill impacts and oil toxicity to Arctic species is extremely limited. Significant research is needed on the behavior of oil spilled in ice-filled seas, the vulnerabilities of Arctic ecosystems to oil toxicity, and the short- and long-term impact of oil spills on Arctic food webs, plants, animals and people. The 2007 Arctic Oil and Gas Assessment Scientific Findings and Recommendations discusses these "gaps in knowledge":

> *"This assessment has identified many gaps in knowledge of the impacts of Arctic oil and gas activities on the environment, biota, and human populations of the Arctic. This is partly due to an incomplete understanding of environmental conditions in the relevant areas of the Arctic and of the species and populations of the many plants and animals that live there as well as their ecological interactions. There is also incomplete knowledge of the socio-economic and health effects on the human populations of the development of the oil and gas industry in the often remote areas. … Research is required on a wide range of the potential biological effects of these chemicals under conditions and with species and life stages appropriate to the Arctic, including, among others, studies of acute and chronic toxicity, genetic effects, and combined effects with, for example, exposure to sunlight. This includes studies of linkages between the diverse sub-lethal effects and the risks they pose to individuals and populations of Arctic animals." (AMAP 2008b)*

Most of the existing knowledge regarding oil toxicity and chemical interactions comes from studies on temperate species. Studies from other cold-water oil spills, such as the Exxon Valdez spill in sub-Arctic Prince William Sound, suggest that oil spill impacts in cold regions can be significant and long-lasting. However, there are many gaps in the current body of knowledge on issues that include:

- Transfer and accumulation of toxic compounds within the Arctic food web.
- Secondary or chronic impacts from oil exposure (e.g. reduced fertility, immuno-suppression).

- Relative sensitivities of various life stages of fish, birds and mammals.
- Photo-enhancement of oil toxicity.
- Seasonal variations in oil toxicity sensitivity among various species.
- Potential impact of global climate change to oil sensitivity and toxicological interactions.

Gaps in existing knowledge regarding oil toxicology to Arctic species must be closed so that leaders can make informed decisions that will not increase the risk of a major oil spill in the U.S. Arctic Ocean. In the Norwegian Barents Sea, a study from 2004 through 2009 added to knowledge on the sensitivity of Arctic species to dispersed oil and produced water (water discharged during oil production, containing some crude oil and other contaminants). The objectives of this study were the following: 1) evaluate the relevance of biomarkers (tools used to evaluate exposure levels to contaminants such as oil) developed for temperate species to sub-Arctic and Arctic species; 2) consider whether biomarkers used in adult species could be applied to juveniles; 3) establish baseline levels for biomarkers in key Arctic species in the Barents Sea region; and 4) collect data that could be used to establish threshold levels for oil exposure based on biomarker levels (Buffagni *et al*. 2010).

The Barents Sea study looked at four fish species in juvenile and adult life cycles. The results of this study are relevant to that region only, but similar research on fish species in the Chukchi and Beaufort Seas might provide a starting point for establishing critical exposure levels to organisms and understanding the potential implications of exposure to spilled oil at various life stages and times of year. Some baseline studies have been conducted in the western nearshore Beaufort Sea to establish baseline hydrocarbon levels in the region of the Northstar gravel island-based production facility (Durell *et al*. 2006).

The impact of oil spills on polynyas and ice leads is another area of Arctic spill science in need of further study. The potential toxicity and adverse effects from alternative response methods such as chemical dispersants and in-situ burning should also be considered.

Considerable additional research should be conducted, and all meetings, reports, and work products should be available for public and stakeholder review and input. All research projects should be developed using peer-reviewed methodologies, and all results should also be peer reviewed.

7.1.2 Improve Spatial Data on Environmental Sensitivities

> *"Ecologically sensitive areas should be mapped, and oil spill trajectory models should be further improved and used to determine areas most at risk from oil spills. This would improve the basis for attempts to decrease or eliminate the probability of an oil spill affecting sensitive areas." (AMAP 2008b)*

Limited information has been compiled to date regarding environmental sensitivities in the U.S. Arctic Ocean. For at least 800,000 years, there has been some sea ice in the Arctic Ocean. Not surprisingly, animals have adapted in many ways to cope with these conditions. At the same time that oil development is being proposed in the offshore Chukchi Sea, Arctic species are facing unprecedented stresses from climate change, which is bringing profound physical and biological impacts. The rapid loss of summer sea ice is having unparalleled effects on the Arctic ecosystem, with some changes already apparent. For example, the distribution of species has begun to shift (Grebmeier *et al*. 2006, Mueter and Litzow 2008) and may alter the structure of Arctic ecology (AMAP2008b, Moore and Huntington 2008). The shrinking of the ice has far-reaching effects on the entire ecosystem, beginning with the phytoplankton that bloom at the ice edge each spring. Climate change is expected to have a "widespread, annual, population-level effect on epontic (under ice) and other lower trophic-level organisms that depend on the summer/autumn ice cover," leading to a major ecological impact at the base of the food chain even without oil exploration and production activities (MMS 2008). The loss of summer sea ice cover has impacts at all levels of the ecosystem, including effects on ice-dependent marine mammals such as walrus (Jay and Fischbach 2008) and polar bear (Hunter *et al*. 2007). Impacts from oil exploration and development, especially the potential for oil spills, will further stress an already fragile ecosystem.

To minimize adverse impacts and assist with response priorities, it is necessary to identify and protect those areas of the ocean with high importance for the ecosystem, ecological processes or species. Important ecological areas (IEAs) can be defined as geographical areas that contribute disproportionately to an ecosystem's health, including its productivity, biodiversity, structure, function or resilience (Ayers *et al.* 2010). Furthermore, these areas may be more at risk to harm and would benefit in the long term from effective management (Ehler and Douvere 2009). However, the Alaskan Arctic Ocean is remote and difficult to access, particularly in the winter months. As a result, IEAs have not been identified for the Chukchi or Beaufort Seas, and many of their species are poorly studied. IEAs in the Arctic seas are expected to be shifting and variable because of seasonal and year-to-year changes in wildlife populations and biological productivity.

Better observation data (wind, current, visibility and ice conditions) should be developed to support oil spill contingency planning and to improve trajectory models. Alaska shore zone mapping and imagery should be expanded to include the Arctic.

Regional oil spill contingency planning should include geographic response strategies (GRS) that identify priority protection sites and provide protective booming strategies and other tactics that may be quickly implemented to protect these areas ahead of a spill trajectory. Currently, sensitive sites are identified, but response tactics and strategies are not tested before exploration and production operations to ensure success. Sufficient resources must be available and dedicated to implement these tactics.

7.1.3 Develop Arctic Oil Spill Trajectory Models

> *"Better knowledge is essential to improve assessments of the transport, fate and effects of spilled oil in ice-covered waters, including oil under ice carried by currents and oil drifting with the sea ice." (AMAP 2008b)*

Better trajectory modeling is needed to develop more realistic oil spill planning scenarios. Existing models have virtually no ability to accurately predict how oil and ice interactions will affect oil movement when sea ice is present (Khelifa 2010). This gap has implications for oil spill planning and response. From a planning perspective, the inability to model oil trajectories during various ice conditions makes it almost impossible for operators or regulators to assess the potential risks from a major oil spill, because we cannot reliably predict where an oil spill would travel and which resources might be affected. If a major spill were to happen during exploration or production operations in the U.S. Arctic Ocean and oil was present in the environment through ice season, responders would have a very limited ability to predict how or where the oil might move.

Improved trajectory modeling will require the collection of more data on environmental and weather conditions for new operating areas such as the Arctic OCS. Additional real-time observation and monitoring systems may need to be developed. This will also require that modelers develop more reliable algorithms to predict how sea ice and oil will interact in the Arctic Ocean.

7.1.4 Consider Cumulative Impacts of Oil Exploration and Production in Arctic OCS

The cumulative impacts of oil exploration and production have been extensively studied in the onshore U.S. Arctic. Proposed expansion of oil exploration and production activities into deeper waters farther offshore from the established Prudhoe Bay oil fields would introduce additional strains on the people and ecology of the region.

It is important to consider the impact of additional activity and infrastructure associated with expanded offshore oil exploration and the development of an enhanced spill response capacity. Roads, docks and other transportation infrastructure can have adverse environmental effects. Changes to the use of coastal areas and OCS waters may affect traditional cultural uses and have unforeseen impacts on indigenous people. Disruptions to traditional lifestyles brought by new infrastructure, disruption of subsistence activities, and an influx of people to the region may all affect the local people.

7.2 Assess and Plan for Worst-Case Blowout Risks

7.2.1 Conduct Risk Assessment

To reduce the risks associated with uncontrolled spills from oil exploration in the Arctic OCS, it is first necessary to conduct a comprehensive risk assessment. There are two components to a risk assessment: conducting a risk analysis that considers the likelihood and consequences of an undesirable event, and identifying risk management measures that target the highest-priority risks.

To calculate risk, a risk analysis is conducted to answer the following questions:

- What can go wrong?
- How likely is it?
- What are the impacts?

The first question is typically answered by developing one or more risk scenarios–in this case, oil spill scenarios that describe what could happen based on the specific operations to be conducted. The second question is answered using a predictive model that estimates the likelihood of occurrence for various types of oil spills that have been identified. The third question requires an analysis of the potential consequences of all possible spill scenarios, based on the sensitivities and vulnerabilities of the local environment, wildlife, culture and socioeconomic resources. The answers derived to these three questions, for all possible scenarios, are a complete expression of the risk being assessed. The result may be expressed quantitatively, qualitatively or through a combined approach.

Significant information-gathering is required to conduct an effective risk analysis. The evaluation of Arctic OCS oil spill risks will require a realistic estimate of oil spill frequency in the offshore Arctic and a synthesis of information about ecological vulnerabilities and environmental sensitivities. It also must include realistic assessments of the potential impacts from catastrophic blowout scenarios that occur in different seasons and conditions.

Expression of risks through a risk analysis is only the first step; the next step is to identify and evaluate risk management options. This requires a prioritization of the identified risks by establishing some criteria for risk tolerance and then evaluating risk reduction measures based on their appropriateness to reduce or mitigate the highest-priority risks.

There are several established methodologies for conducting oil spill risk assessments. A project is ongoing in the Aleutian Islands using a methodology suggested by the National Academy of Sciences. A similar process could be applied to the Arctic Ocean.

7.2.2 Require More Realistic Worst-Case Blowout Scenarios

Worst-case discharge amounts–the maximum spill size that could occur from exploration or production operations–should be calculated on the basis of the highest possible flow rates for a well, based on all available data. Higher "default" flow rates should be established for operations in new regions such as the Arctic OCS—where previous offshore exploration has confirmed that blowouts could exceed (by several orders of magnitude) the state response planning standard of 5,500 barrels of oil per day (bopd)—and based on well data from similar reservoirs located onshore. Worst-case discharge estimates should also factor in the time required to stop the blowout. The Deepwater Horizon blowout continued for three months. Other blowouts have lasted longer, yet many oil spill contingency plans consider only a 15- or 30-day duration.

7.2.3 Improve Oil Spill Prevention Technologies for Arctic Exploration and Production

Blowout prevention technologies and blowout control measures should also be assessed, because blowout control is the first line of defense against a major oil spill.

Additional requirements for reducing blowout risks and improving blowout control in the Arctic may include:

- Arctic design standards and best practices. All equipment used for oil exploration and production in the Arctic Ocean, including but not limited to vessels, pipelines, wells, tanks, processing equipment and structures, should be designed in accordance with Arctic engineering practices and should be able to withstand worst-case geological hazards, Arctic temperatures, wind, water and ice hazards that may be encountered. Design criteria should be based on actual measurements of worst-case data for the site of development, or on conservative estimates. If operations are planned during ice conditions, vessels should be certified by the U.S. Coast Guard or the American Bureau of Shipping as Arctic Class and should be capable of operating safely in Arctic conditions.
- Emergency shutdown devices (ESD). ESDs should be installed on the offshore drilling units and facilities to limit the scope of any single failure. Manual and automatic ESDs should be installed to allow operators to manually shut down systems, or to allow systems to automatically shut down if operators are unable to safely access the system. ESDs should be provided for all the primary systems of a drilling unit's operation and facility operation and for fuel transfers. ESD systems should be tested before use and at regular intervals thereafter.
- Blowout prevention systems (BOPs). BOP systems should be capable of controlling at least 150 percent of the maximum anticipated pressure; equipped with two sets of blind shear rams; inspected by the manufacturer and an independent third-party certified inspector before use; tested on a seven-day interval versus the current requirement of 14 days; and have reliable emergency backup control systems and immediate access to sufficient remote operating vehicles to manually activate a subsea BOP if needed. Shear rams should be tested on the pipe planned for use to verify capability to sever that grade of pipe. Redundant BOPs should be considered and installed for floating drilling units when technically feasible.
- Backup drilling rigs on site. To facilitate relief well drilling in the event of a blowout, operators should be required to have a drilling rig on standby to initiate relief well drilling and to have purpose-built well capping structures (such as the one used during the Deepwater Horizon blowout) prefabricated and available on site before drilling begins. Oil spill removal organizations (OSRO) operating in the Arctic OCS should demonstrate that they have sufficient regional capacity to support an Arctic OCS well blowout. Resident blowout control capabilities are needed in the U.S. Arctic. Well control equipment and experts should be on site to take immediate action to control the well and/or contracts should be in place with well control experts to immediately bring additional personnel, equipment and expertise to the site in the event of a blowout.
- Pre-fabricated containment structures. Containment structures must be designed, engineered, and tested under Arctic conditions. Such structures—if they can be

successfully engineered to withstand the ice and weather conditions in the Arctic Ocean—should be part of the toolkit for any operators drilling in the U.S. Arctic Ocean.

7.3 Improve Arctic OCS Oil Spill Response Capacity

7.3.1 Assess Existing Oil Spill Response Capacity for Oil Spills in Arctic OCS

To develop the response capacity needed to support offshore exploration and production in the Arctic OCS, it is necessary first to assess the capabilities of available oil spill response systems, to delineate the upper operating limits of equipment and systems, and to identify opportunities to improve responsibilities, while also establishing prevention measures to minimize spill risks when response capacity may be exceeded. This process should occur before oil exploration activities introduce the risk of a catastrophic spill to the Arctic OCS.

Oil spill response capacity is much more than spill response equipment, particularly for offshore areas where on-water response requires considerable logistical support. In addition to the booms, skimmers and recovered oil storage devices that make up a typical offshore or nearshore spill response task force, the capacity also includes: the vehicles and vessels that transport the equipment from its storage location to the spill site; the workboats, barges, cranes and other support equipment that are used to support the on-water response operations; the personnel required to operate vehicles and vessels, run equipment, and direct the response operations; and the tactical plans that outline how all of these components will operate to achieve oil spill containment, recovery and cleanup objectives.

Assessing the effectiveness and limitations of oil spill response capacity for a given operation or operating area requires complex analysis. To a certain extent, this can be accomplished on paper by conducting scenario analyses in which a specific spill size, location and trajectory are used to map out how and where resources would be applied during a spill, and to assess how much of the spilled oil the available resources might be able to recover. However, most oil spill response scenarios are predicated on a set of assumptions that require validation through field deployment exercises (See discussion Section 7.2.2).

7.3.2 Require Operators to Demonstrate Oil Spill Response Capabilities during Agency-Led Field Exercises

There is little real-world information available regarding the effectiveness of Arctic spill response systems because there have been no major Arctic offshore oil spills. Most of our assumptions about how spill response systems will perform in the Arctic OCS are derived from small-scale laboratory and tank tests, or field tests that are limited to a specific piece of equipment. The information gleaned from such tests may be misleading; for example, a tank test demonstrating that a skimmer will not clog until ice concentrations exceed 40 percent coverage does not mean that the full oil spill recovery system–vessels, boom, skimmer and storage barge–could operate safely or effectively up to that limit. The upper limit of a single piece of equipment or an individual technology does not guarantee that the response system required to deploy that technique will have the same functionality.

Government approval of oil spill contingency plans should be based upon demonstrated capabilities verified through field exercises, unannounced drills and audits. One necessity is full-scale field trials, during which multiple vessels are deployed to test tactics in Arctic OCS waters and ensure that all components of a response system can operate effectively, and then to delineate the upper operating limits posed by environmental conditions such as wind, sea state, sea ice and visibility.

During full-scale field deployments, equipment is transported to the scene and deployed under a range of natural conditions. In some cases, a response system may fail not because of a primary equipment malfunction, but because one (or more) of the technologies or support platforms does not perform as intended. These support functions may be severely challenged by Arctic environmental conditions, remote locations or lack of infrastructure. During a series of field trials held in the Alaska Beaufort Sea, responders found that the actual limits to a vessel-based skimming and recovery system were realized in much lower sea ice concentrations than previously assumed.

Multi-agency oversight of these drills and written documentation will help to build a knowledge base regarding the limits to oil spill response systems in the Arctic OCS. The plan review and approval process for all OCS oil spill response plans should include an opportunity for public review and comment and also should include consultation among agencies with roles in oil spill prevention and response as well as natural resource trustees.

7.3.3 Improve On-Water Oil Spill Response Systems and Techniques for Arctic OCS Conditions

Oil spill cleanup technologies have been slow to improve, and the basic tools used to contain and remove oil spills today are very similar to those in place decades ago. The Deepwater Horizon incident led to a number of innovations, forced by the imminent pressure of an exploding oil well. Moving forward, a more comprehensive and proactive research and development regime should be designed to expand the limits of existing spill response technologies, particularly mechanical recovery, the only technique that removes oil from the environment. Programs such as the JIP are a first step in this process, though the JIP had many flaws, including a lack of peer review and a lack of transparency during the research. Spill response technologies have not kept pace with advances in drilling technologies.

New technologies for subsea containment, such as the one developed and used during the Deepwater Horizon spill, should be developed for the Arctic Ocean.

7.4 Conduct an Arctic OCS Oil Spill Response Gap Analysis

A response gap exists whenever environmental conditions exceed the operating limits of oil spill cleanup equipment, meaning that if a spill occurred during this time, it could not be contained or cleaned up. Although it is clear that the environmental, oceanographic and climatic conditions in the Arctic Ocean represent a challenge to existing oil spill cleanup technologies, the extent to which these conditions might limit oil spill cleanup is not well understood. An Arctic oil spill response gap analysis will provide critical information regarding the oil spill response limits posed by Arctic environmental conditions (temperature, wind, sea ice, visibility) and will calculate how frequently those operating limits are reached in the area of oil exploration and production operations.

The methodology for conducting such an analysis involves three key steps:

Quantify the operating limits of offshore oil spill response systems available to clean up oil spills in the Arctic. This process starts with examination of one or more offshore spill response systems (equipment, vessels and personnel) and then consideration of the upper operating limits of that system or systems. This is typically determined by the component (or components) that is most likely to fail once a given condition—sea state, ice coverage, visibility, temperature or wind—is exceeded. When that limit is exceeded, the response system would be rendered inoperable.

Calculate the frequency with which the operating limit is reached. Historical weather data and observations are analyzed to determine how frequently each of the limiting factors occurs during the operating season. If historical data are not available, modeling may be used. Assuming that multiple factors would limit Arctic offshore spill response operations, the analysis would also have to consider the interplay among factors to account for any cumulative impacts. (For example, the combination of 10 percent ice coverage and less than 1 nautical mile visibility may present an operating limit, even though individually neither factor represents an upper limit.)

Estimate the response gap by applying the operating limits to the environmental dataset. The result of this analysis will characterize the frequency of occurrence of one or more environmental factors that would render oil spill cleanup possible, impaired or impossible. Such an analysis was completed in Prince William Sound in Alaska in 2007, showing that during the winter season at one offshore location, a response gap existed 65 percent of the time.

There is no question that a response gap exists in the Arctic. Once it has been estimated, additional oil spill prevention or mitigation measures may then be put into place to reduce the likelihood of a spill occurring when no response is possible.

8 REFERENCES

Abdelnour, R., and G. Comfort. (2001). *Application of ice booms for oil-spill cleanup in ice infested waters*. Fleet Technology Ltd. Kanata, Ontario.

Alaska Clean Seas. (2009). *Technical Manual*. Prudhoe Bay, Alaska.

Alaska Department of Environmental Conservation. (March 28, 2006). *Situation Report: GC-2 Oil Transit Line Release* (SitRep #19).

Albers, P.H. (2003). Petroleum and individual polycyclic aromatic hydrocarbons. In: D.J. Hoffman, B.A. Rattner, G.A. Burton Jr. and J. Cairns Jr. (eds.). Handbook of Ecotoxicology, second edition. Pp. 341-371.

Allan, R., *et al.* (2009). *A goal-based solution to offshore drilling challenges in Arctic environments.* Offshore Technology Conference 19954. Pp. 1-7.

Anderson, A. (Sept. 1, 2010). Arctic oil and gas drilling ready to take off. *NewScientist*. www.newscientist.com/article/mg20727764.300-arctic-oil-and-gas-drilling-ready-to-take-off.html.

Anderson, E., and W. Talley. (May 1995). The oil spill size of tanker and barge accidents: Determinants and policy implications. *Land Economics* 71(2):216-228.

American Petroleum Institute. (2004). *In-situ burning: The fate of burned oil.* API Publication 4735.

Arctic Council. (2009). *Arctic Marine Shipping Assessment 2009.* Oslo, Norway.

Arctic Monitoring and Assessment Programme. (1998). *Assessment Report: Arctic Pollution Issues.* Arctic Council Report. Oslo, Norway.

Arctic Monitoring and Assessment Programme. (2002). *Assessment 2002: Persistent organic pollutants in the Arctic.* Arctic Council Report. Oslo, Norway.

Arctic Monitoring and Assessment Programme. (2008a). *Arctic Oil and Gas 2007.* Arctic Council Report. Oslo, Norway.

Arctic Monitoring and Assessment Programme. (2008b). *Assessment 2007—Oil and Gas in the Arctic: Effects and Potential Effects.* Arctic Council Report. Oslo, Norway.

(Photo credit: Coastline, *Ground Truth Trekking, 2010*)

Arhelger, S.D., *et al.* (1977). Arctic hydrocarbon biodegradation. In: D.A. Wolfe (ed.). *Fate and Effects of Petroleum Hydrocarbons in Marine Organisms and Ecosystems*, Pp. 270-275. Pergamon Press, Oxford.

Atlas, R.M. (1985). Effects of hydrocarbons on microorganisms and petroleum biodegradation in Arctic ecosystems. In: F.R. Engelhardt (ed.). *Petroleum effects in the Arctic environment*. Pp. 63-99. London: Elsevier Applied Science Publishers.

Ayers, J.A., *et al.* (2010). *Important ecological areas in the ocean: A comprehensive ecosystem protection approach to the spatial management of marine reserves.* Oceana Discussion Paper. Aug. 23, 2010. Juneau, Alaska.

Barron, M. (March 9, 2000). *Potential for Photoenhanced Toxicity of Spilled Oil in Prince William Sound and Gulf of Alaska Waters*. Report prepared for Prince William Sound Regional Citizens' Advisory Council. Anchorage, Alaska.

Barron, M.G., *et al.* (2003). *Assessment of the phototoxicity of weathered Alaska North Slope crude oil to juvenile pink salmon*. Contract No. 955.03.3. Final report prepared for the Prince William Sound Regional Citizens' Advisory Council. Anchorage, Alaska.

Bobra, A.M., and M.F. Fingas. (1986). The behavior and fate of Arctic oil spills. *Water Science Technology* 18(2):13-23.

BP Exploration Alaska. (May 2003). *Northstar Oil Discharge Prevention and Contingency Plan—Best Available Technology (Part 4)*. Revision 2.

BP Exploration and Production Inc. (Feb. 23, 2009). *Initial exploration plan: Mississippi Canyon Block 252, OCS-G 32306*. Prepared for the Minerals Management Service.

Braddock, J.F., *et al.* (2004). Petroleum hydrocarbon-degrading microbial communities in Beaufort-Chukchi Sea Sediments. Report OCS Study MMS 2004-061, 43pp.

Brandvik, P.J., *et al.* (2006). *Short state-of-the-art report on oil spills in ice-infested waters: Oil behavior and response options.* SINTEF Group. May 19.

Brandvik, P.J., *et al*. (2010a). Mapping weathering properties as a function of ice conditions: A combined approach using a flume basin verified by large-scale field experiments. *Proceedings of the 33rd Arctic Marine Oil Spill Program Technical Seminar on Environmental Contamination and Response*. Halifax, Nova Scotia. Environment Canada. Pp. 701-724.

Brandvik, P.J., *et al.* (2010b). Using a small scale laboratory burning cell to measure ignitability for in-situ burning of oil spills as a function of weathering. *Proceedings of the 33rd Arctic Marine Oil Spill Program Technical Seminar on Environmental Contamination and Response*. Halifax, Nova Scotia. Environment Canada. Pp. 755-772.

Brandvik, P.J., *et al.* (2010c). Predicting ignitability for in-situ burning of oil spills as a function of oil type and weathering degree. *Proceedings of the 33rd Arctic Marine Oil Spill Program Technical Seminar on Environmental Contamination and Response*. Halifax, Nova Scotia. Environment Canada. Pp. 773-787.

Brower, W., *et al*. (1988). *Climatic Atlas of the Outer Continental Shelf Waters and Coastal Regions of Alaska*. Anchorage, Alaska: Arctic Environmental Information and Data Center, University of Alaska. 519 pp.

Brower Sr., T.P. (Oct. 10, 1978). Sworn Affidavit as Part of the Public Record of Testimony Concerning the Proposed State of Alaska Pt. Thompson Lease Sale, Anchorage, Alaska: Alaska Department of Natural Resources, Division of Oil and Gas.

Brown, E.D., and M.G. Carls. (September 1998). Pacific herring. Restoration Notebook, Exxon Valdez Oil Spill Trustee Council. Pp. 1-8.

Buffagni, M., *et al.* (2010). *Environmental risk management of the E&P operations in the Barents Sea: Environmental indicators and threshold levels*. Society of Petroleum Engineers. SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production. Rio de Janeiro. April 12-14, 2010.

Buist, I., *et al.* (1997). Laboratory studies of the properties of in-situ burn residues. *Proceedings of the 1997 International Oil Spill Conference*. Pp. 149-156.

Buist, I., *et al.* (2003). Tests to determine the limits to in situ burning of thin oil slicks in brash and frazil ice. *Proceedings of the 26th Arctic and Marine Oil Spill Program Technical Seminar.* Environment Canada, Ottawa, Ontario. June 10-12, 2003.

Buist, I., *et al.* (2006). *Mid-scale tank test research on using oil herding surfactants to thicken oil slicks in pack ice: An update.* Arctic Marine Oil Spill Program. Environment Canada.

Buist, I., *et al.* (2010a). New herding agents for thickening oil slicks in drift ice for in-situ burning. Arctic Marine Oil Spill Program. *Proceedings of the 33rd Arctic Marine Oil Spill Program Technical Seminar on Environmental Contamination and Response*. Halifax, Nova Scotia. Environment Canada. Pp. 1085-1108.

Buist, I., *et al.* (2010b). Barents Sea field test of herder to thicken oil for in-situ burning in drift ice. Arctic Marine Oil Spill Program. *Proceedings of the 33rd Arctic Marine Oil Spill Program Technical Seminar on Environmental Contamination and Response*. Halifax, Nova Scotia. Environment Canada. Pp. 725-742.

Bureau of Energy Management, Regulation and Enforcement. (June 21, 2010). Salazar swears-in Michael Bromwich to lead Bureau of Energy Management, Regulation and Enforcement. www.boemre.gov/ooc/press/2010/press0621.htm.

Burns, J.J., *et al.* (June 1980). The relationship of marine mammal distributions, densities and activities to sea ice conditions. Pp. 489-670. In: *Outer Continental Shelf Energy Assessment Program, Volume II: Biological Studies*.

Clark, R.B. (1984). Impact of oil pollution on seabirds. *Environmental Pollution Series A* 33:1-22.

CNN. (2010). BP: Relief well may be ready by end of July. http://amfix.blogs.cnn.com/2010/07/07/bp-relief-well-may-be-ready-by-end-of-july.

Common petroleum safety standards. (Dec. 20, 2009). *The BarentsObserver.* www.barentsobserver.com/common-petroleum-safety-standards.4666871-16176.html. Accessed July 9, 2010.

Conlan, K.E., *et al.* (1998). Ice scour disturbances to benthic communities in the Canadian High Arctic. *Marine Ecology Progress Series* 166:1-16.

Culbertson, J.B., *et al.* (2007). Long-term biological effects of petroleum residues on fiddler crabs in salt marshes. *Marine Pollution Bulletin*. In press.

Daling, P.S., *et al.* (2010). *Development and field testing of a flexible system for application of dispersants on oil spills in ice.* Arctic Marine Oil Spill Program. Environment Canada. Pp. 787-814.

Dauvin, J.-C. (1989). Life cycle, dynamics and productivity of Crustacea-Amphipoda from the western English Channel. 5. *Ampelisca sarsi* Chevreux. *Journal of Experimental Marine Biology and Ecology* 128(1):31-56.

DeCola *et al*. (2006). Offshore Oil Spill Response in Dynamic Ice Conditions: A Report to WWF on Considerations for the Sakhalin II Project.

Department of Energy/National Energy Technology Laboratory. (August 2007). *Alaska North Slope Oil & Gas: A Promising Future or an Area in Decline?* (2007/1280 Summary Report). Fairbanks, Alaska.

Details of Alaska blowouts. (Dec. 19, 2008). *Anchorage Daily News*. www.adn.com/2008/12/18/628170/details-of-alaska-blowouts.html.

D.F. Dickins Associates Ltd. (March 2004). *Advancing oil spill response in ice-covered waters.* Prepared for the Prince William Sound Oil Spill Recovery Institute and U.S. Arctic Research Commission. Anchorage, Alaska.

D.F. Dickins Associates Ltd. and Fleet Technology Ltd. (March 1992). *Behavior of Spilled Oil at Sea (BOSS). Oil-in-ice fate and behavior.* Prepared for Environment Canada.

Dickins, D., and Buist, I. (1999). Countermeasures for ice-covered waters. *Pure Applied Chemistry* 71(1):173-191.

Dickins, D., *et al.* (2010). *Remote sensing for the oil in ice Joint Industry Program 2007-2009.* Arctic Marine Oil Spill Program. Environment Canada. Pp. 815-840.

Durell, G., *et al.* (2006). Monitoring the impact of near-shore development and production in the Arctic Beaufort Sea, Alaska. *Society of Petroleum Engineers*. 98500. Pp. 1-8.

Edwards, R., and I. White. (1999). The Sea Empress oil spill: Environmental impact and recovery. *Proceedings of the 1999 International Oil Spill Conference.* Seattle. March 7-12, 1999. Pp. 97-102.

Ehler, C., and F. Douvere. (2009). *Marine Spatial Planning: A step-by-step approach toward ecosystem-based management*. Intergovernmental Oceanographic Commission and Man and the Biosphere Programme. IOC Manual and Guides No. 53, ICAM Dossier No. 6. Paris: UNESCO.

Eicken, H., *et al.* (2006). *Mapping and Characterization of Recurring Spring Leads and Landfast Ice in the Beaufort and Chukchi Seas*. Prepared for Minerals Management Service, Anchorage, Alaska.

Engelhardt, F.R. (1987). Assessment of the Vulnerability of Marine Mammals to Oil Pollution. *Proceedings of the Conference on Oil Pollution.* Organized under the auspices of the International Association on Water Pollution Research and Control by the Netherlands Organization for Applied Scientific Research. Feb. 23-27, 1987. Boston. Pp. 101-115.

Evers, K., *et al. (*2004). *State of the art report on oil weathering and on the effectiveness of response alternatives.* Prepared for Arctic Operational Platform.

Evers, K., *et al.* (2006). *Oil spill contingency planning in the Arctic—Recommendations.* Prepared for Arctic Operational Platform.

Fairweather E&P Services Inc. (June 2000). *Historical Blowout Study: North Slope, Alaska*. Prepared for BP-Amoco Exploration, Alaska.

Faksness, L., *et al.* (2010). *The monitoring of oil in water and MetOcean interactions during a large-scale oil-in-ice experiment in the Barents Sea.* Arctic Marine Oil Spill Program. Environment Canada. Pp. 679-700.

Fay, F.H. (June 1981). *Modern populations, migrations, demography, trophics and historical status of the Pacific walrus: Annual Report Environmental Assessment of the Alaskan Continental Shelf, annual reports of principal investigators for the year ending March 1981. Volume 1: Receptors—Birds, Fish, Marine Mammals, Plankton, Littoral.*

Fay, F.H. (1982). Ecology and biology of the Pacific walrus *Odobenus rosmarus divergens Illiger*. *North American Fauna* 74. U.S. Department of the Interior, Fish and Wildlife Service.

Fay, F.H. (1985). *Odobenus rosmarus*. Mammalian Species No. 238. American Society of Mammalogists. P. 7.

Fay, F.H., *et al.* (1984). Modern populations, migrations, demography, trophics, and historical status of the Pacific walrus. In: *Outer Continental Shelf Environmental Assessment Program, Final Reports of Principal Investigators* 37:231-376 RU 0611.

Fingas, M. (2001). *The basics of oil spill cleanup* (second edition). J. Charles (ed.).

Fingas, M. (2004). Weather windows for oil spill countermeasures. Prepared for Prince William Sound Regional Citizens' Advisory Council.

Fingas, M., *et al.* (1994). The Newfoundland Offshore Burn Experiment: NOBE preliminary results of emissions measurement. *Proceedings of the 17th Arctic and Marine Oil Spill Program Technical Seminar.* Pp. 1099-1164.

Fingas, M.F., and B.P. Hollebone. (2003). Review of the behavior of oil in freezing environments. *Marine Pollution Bulletin* 47:333-340.

Fontneau, C.S. (February 1990). *An Oceanographic and Climatological Atlas of the Chukchi Sea.* Report No. CG-D-08-91.

Frost, K.J., and L.F. Lowry. (1994). *Assessment of injury to harbor seals in Prince William Sound, Alaska, and adjacent areas following the Exxon Valdez oil spill*. State and Federal Natural Resource Damage Assessment Final Report. Marine Mammal Study No. 5, Restoration Study No. 73.

Fuller, C., and J.S. Bonner. (2001). Comparative toxicology of oil, dispersant and dispersed oil to Texas marine species. *Proceedings of the 2001 International Oil Spill Conference*. Pp. 1243-1241.

Gaida, K.P., *et al.* (1983). Kulluk—An Arctic exploratory drilling unit. Offshore Technology Conference 4481. Pp. 337-346.

Gaston, A.J., and I.L. Jones. (1998). *The Auks*. Oxford University Press. 349 pp.

Glover, N., and D. Dickins. (1999). *Oil spill response preparedness in the Alaska Beaufort Sea.* Reprint of material presented in 1996 Symposium on Oil Spill Prevention and Response and 1999 International Oil Spill Conference.

Grace, R.D. (2003). *Blowout and Well Control Handbook*. Gulf Professional Publishing.

Grebmeier, J.M., *et al.* (March 10, 2006). A major ecosystem shift in the northern Bering Sea. *Science* 311(5766):1461-1464.

Grebmeier, J.M., *et al.* (2010). Biological response to recent Pacific Arctic sea ice retreats. *EOS* 91(18):161-162.

Gulec, I., and D.A. Holdway. (1997). Toxicity of dispersant, oil and dispersed oil to two marine organisms. *Proceedings of the 1997 International Oil Spill Conference*. Pp. 1010-1011.

Hassol, S. (2004). *Impacts of a warming Arctic*. Arctic Climate Impact Assessment. AMAP, CAFF and IASC. Cambridge University Press.

Highsmith, R.C., and K.O. Coyle. (July 16, 1992). Productivity of Arctic amphipods relative to gray whale energy requirements. *Marine Ecology Progress Series* (83):141-150.

Hinkel, R.M., *et al.* (1988). Experience with drillship operations in the U.S. Beaufort Sea. Offshore Technology Conference 5685. Pp. 35-48.

Hoff, G.C., *et al.* (1994). *Proceedings of the Fourth International Offshore and Polar Engineering Conference*. Vol. 1. International Society of Offshore and Polar Engineers. Golden, Colo. Pp. 1-7.

Hsiao, S.I.C. (1978). Effects of crude oils on the growth of Arctic marine phytoplankton. *Environmental Pollution* 17:93-107.

Humphrey, B., *et al.* (1987). The fate of chemically dispersed untreated crude oil in Arctic benthic biota. *Arctic* 40 (Supp. 1):49-161.

Hunter, C.M., *et al.* (2007). *Polar bears in the southern Beaufort Sea II: Demography and population growth in relation to sea ice conditions.* Prepared for the U.S. Geological Survey Science Strategy to Support U.S. Fish and Wildlife Service Polar Bear Listing Decision.

Integral Consulting Inc. (2006). *2005 Assessment of lingering oil and resource injuries from the Exxon Valdez oil spill*. Final report Exxon Valdez Oil Spill Restoration Project. (Restoration Project 0440776), Mercer Island, Wash. www.evostc.state.ak.us/projects/ProjectInfo.cfm?project_id=211.

International Arctic Research Center. (2005). *Coastal climatology and extreme weather events in Alaska and the Arctic.* (March 31, 2005). University of Alaska, Fairbanks. www.iarc.uaf.edu/highlights/2005/coastal_climate/index.php.

Jay, C.V., and A.S. Fishbach. (2008). Pacific walrus response to Arctic sea ice losses. U.S. Geological Survey Fact Sheet 2008-3041. http://pubs.usgs.gov/fs/2008/3041.

Joint Industry Subsea Well Control and Containment Task Force (Sept. 3, 2010). *Draft industry recommendations.* www.scribd.com/doc/37060248/Joint-Industry-Subsea-Well-Control-and-Containment-Task-Force-Draft-Industry-Recommendations.

Joint Information Center. (2010). *The ongoing administration-wide response to the BP Deepwater oil spill.* https://www.piersystem.com/go/doc/2931/767655.

Kelly, M.J., and L. Flak. (2006). *Blowout surface intervention methods: Description of debris removal techniques; special services like junk shots, hot tapping and freezing; and proven methods of well capping.* www.jwco.com/technical-literature/p10.htm.

Keener, C., and R. Allan. (2009). *A seasonal solution for offshore drilling in an ice environment.* International Association of Drilling Contractors/Society of Petroleum Engineers 119818. Pp. 1-9.

Khelifa, A. (2010). A summary review of modeling oil in ice. *Proceedings of the 33rd AMOP Technical Seminar on Environmental Contamination and Response*. Environment Canada. June 7-9, 2010. Halifax, Nova Scotia.

Landrum, P.F., *et al*. (1987). Photoinduced toxicity of polycyclic aromatic hydrocarbons to aquatic organisms. In: J.H. Vandermeulen and S.E. Hrudey (eds.). *Oil in Freshwater: Chemistry, Biology, Countermeasure Technology,* Pergamon Press. Pp. 304-318.

Lindstrom, J.E., D.M. White and J.F. Braddock. (1999). *Biodegradation of Dispersed Oil Using COREXIT 9500.* Report prepared for the Alaska Department of Environmental Conservation Division of Spill Prevention and Response. June 30, 1999, Fairbanks, Alaska. www.dec.state.ak.us/spar/perp/r_d/biodeg.pdf.

Lubchenco, J., *et al. BP Deepwater Horizon oil budget: What happened to the oil?* Prepared for the Deepwater Horizon Unified Command.

Majewski, H.S., and E. Scherer. (1985). Uptake and depuration of two polycyclic aromatic hydrocarbons, fluorene and benzo[*a*]pyrene, in the mussel *Mytilus edulis* and the diatom *Phaeodactylum tricornutum*. *Water Pollution Research Journal of Canada* 20(2):29-35.

Martinelli, M., *et al.* (1995). The M/C Haven oil spill: Environmental assessment of exposure pathways and resource injury. *Proceedings of the 1995 International Oil Spill Conference.* Pp. 679-685.

Masterson, D.M., *et al.* (1991). *Beaufort Sea exploration: Past and future*. Offshore Technology Conference 6530. Pp. 9-25.

Matkin, C.O., *et al.* (March 18, 2008). Ongoing population-level impacts on killer whales *Orcinus orca* following the Exxon Valdez oil spill in Prince William Sound, Alaska. *Marine Ecology Progress Series*. 256.

Matskevitch, D.G. (2007). *Technologies for Arctic offshore exploration and development*. Society of Petroleum Engineers 102441. Pp. 1-6.

Minerals Management Service. (2007a). *Chukchi Sea planning area oil and gas Lease Sale 193 and seismic surveying activities in the Chukchi Sea*. Final Environmental Impact Statement. OCS EIS/EA MMS 2007-026. Vol. 1. www.arlis.org/docs/vol1/140350076/140350076v1.pdf.

Minerals Management Service. (2007b). *Outer continental shelf oil and gas leasing program 2007-2012*. Final Environmental Impact Statement. OCS EIS/EA MMS 2007-003. www.boemre.gov/5-year/2007-2012FEIS/Chapter3AffectedEnvironment.pdf

Minerals Management Service. (2008). *Beaufort and Chukchi Sea planning areas oil and gas Lease Sales 209, 212, 217 and 221*. http://alaska.boemre.gov/ref/EIS EA/ArcticMultiSale_209/_DEIS.htm.

Minerals Management Service. (2010). *Shell Gulf of Mexico Inc.—Chukchi Sea Project*. http://alaska.mms.gov/ref/ProjectHistory/2009_Chukchi_Shell/Chukchi_2009.HTM. Accessed June 24, 2010.

Moles, A., *et al.* (2002). Effectiveness in the Laboratory of Corexit 9527 and 9500 in dispersing fresh, weathered and emulsion of Alaska North Slope crude oil under subarctic conditions. *Spill Science and Technology Bulletin.* 7(5-6):241-247.

Moore, S.E., and H.P. Huntington. (2008). Arctic marine mammals and climate change: Impacts and resilience. *Ecological Applications* 18(2):S157-S165.

Mueter, F.J., and M.A. Litzow. (2008). Sea ice retreat alters the biogeography of the Bering Sea Continental Shelf. *Ecological Applications* 18(2):309-320.

National Oceanic and Atmospheric Administration. (2009). (Graph illustration from the National Weather Service Forecast Office for Portland, Ore.) *Estimating Wind Speed and Sea State.* www.wrh.noaa.gov/pqr/info/beaufort.php. Retrieved July 9, 2010.

National Oceanic and Atmospheric Administration Office of Response and Restoration. (2005). *In situ burning.* http://response.restoration.noaa.gov/topic_subtopic_entry.php?RECORD_KEY%28entry_subtopic_topic%29=entry_id,subtopic_id,topic_id&entry_id(entry_subtopic_topic)=225&subtopic_id(entry_subtopic_topic)=8&topic_id(entry_subtopic_topic)=1. Accessed May 24 2010.

National Research Council. (1985). *Oil in the Sea*. Inputs, Fates and Effects. National Academies Press. 601 pp.

National Research Council. (1989). *Using oil dispersants on the sea*. Washington: National Academies Press.

National Research Council. (2003a). *Oil in the sea III: Inputs, fates and effects*. Washington: National Academies Press.

National Research Council. (2003b). *Cumulative environmental effects of oil and gas activities on Alaska's North Slope*. Washington: National Academies Press.

National Response Team. Science and Technology Committee. (1997). *Site safety plans for marine in situ burning operations*. Fact sheet. 6 pp.

National Snow and Ice Development Center. (2010). Arctic sea ice news and development. http://nsidc.org/Arcticseaicenews. Accessed Aug. 4, 2010.

Native Village of Point Hope et al. v. Kenneth L. Salazar et al. U.S. District Court, District of Alaska. Filed Aug. 2, 2010. Case 1:08-cv-0004-RRB.

Native Village of Point Hope et al. v. Salazar, Case 09-73942. Denied. U.S. Court of Appeals for the 9th Circuit, 2010.

North Pacific Fishery Management Council. (August 2009). *Fishery management plan for fish resources of the Arctic management area.* North Pacific Fishery Management Council, Anchorage, Alaska. www.fakr.noaa.gov/npfmc/fmp/arctic/ArcticFMP.pdf.

Nuka Research and Planning Group LLC. (2006). *Response Gap Methods.* Report to Prince William Sound Regional Citizens' Advisory Council. Anchorage, Alaska. www.pwsrcac.org/docs/d0027800.pdf

Nuka Research and Planning Group, LLC. (2007a). *Oil Spill Response Challenges in Arctic Waters.* Report to WWF International Arctic. http://assets.panda.org/downloads/nuka_oil_spill_response_report_final_jan_08.pdf

Nuka Research and Planning Group LLC. (2007b). *Oil Spill Response Mechanical Recovery Systems for Ice-Infested Waters: Examination of Technologies for the Alaska Beaufort Sea.* Report to Alaska Department of Environmental Conservation. www.dec.state.ak.us/spar/ipp/docs/2007%20Mechanical%20Recovery%20Ice.pdf

Nuka Research and Planning Group LLC. (2008). *Non-Mechanical Response Gap Estimate for Two Operating Areas of Prince William Sound, Alaska.* Report to Prince William Sound Regional Citizens' Advisory Council. Anchorage, Alaska. www.pwsrcac.org/docs/d0046700.pdf.

Ocean Studies Board. (2005). *Oil spill dispersants: Efficacy and effects.* Committee on Understanding Oil Spills: Efficacy and Effects. National Research Council. Washington: National Academies Press.

Oil Rig Disasters. http://home.versatel.nl/the_sims/rig/index.htm. Accessed September 2010.

Owens, E.H., *et al.* (1998). *Field guide for oil spill response in Arctic waters.* Prepared for Emergency Prevention, Preparedness and Response Working Group, Arctic Council.

Owens, E., *et al.* (2005). The behavior and documentation of oil spilled on snow- and ice-covered shorelines. *Proceedings from the International Oil Spill Conference.* Miami. May 15-19, 2005.

PTT Exploration and Production Co. Australasia Ltd. (No date). Commission of inquiry; Montara well head platform; uncontrolled hydrocarbon release. www.montarainquiry.gov.au/downloads/21%20PTTEP/SUBM.1000.0002.0026.pdf.

Parker, M.W., *et al*. (2007). Assessment of social attraction techniques used to restore a common murre colony in central California. *Waterbirds* 30(1):17-28.

Paulin, M.J., *et al.* (2010). Arctic offshore technology assessment of exploration and production options for cold regions of the U.S. continental shelf. Oil Technology Conference 20698. Pp. 1-16.

Peterson, C.H., *et al.* (Dec. 19, 2003). Long-term ecosystem response to the Exxon Valdez oil spill. *Science* 302(5653):2082-2086.

Petterson, J.S., and E.W. Glazier. (2004). *A study of the drift gillnet fishery and oil/gas industry interactions and mitigation possibilities in Cook Inlet.* Prepared for the Minerals Management Service. OCS Study MMS 2004-038.

Potter, S. (ed.). (2004). *World catalog of oil spill response products.* Ottawa, Ontario. S.L. Ross Environmental Research Ltd. Eighth edition. 2004-2005.

Potter, S., and I. Buist (2010). *In-situ burning in Arctic and ice-covered waters: Tests of fire-resistant boom in low concentrations of drift ice.* Arctic Marine Oil Spill Program. Environment Canada. Pp. 743-754.

Prince, R.C., *et al.* (2002). Weathering of an Arctic oil spill over 20 years: The BIOS experiment revisited. *Marine Pollution Bulletin.* 44(11):1236-1242.

Reed, M., *et al.* (1999). Oil spill modeling towards the close of the 20th century: Overview of the state of the art. *Spill Science and Technology Bulletin* 5(1):3-16.

Regg, J.B., and R.Y. Kuranel. (1992). *Minerals Management Service regulation of floating drilling unit operations in the Beaufort and Chukchi outer continental shelf.* International Association of Drilling Contractors/Society of Petroleum Engineers 23922. Pp. 703-712.

Richter-Menge, J., *et al.* (2008). *Arctic Report Card 2008*. www.arctic.noaa.gov/report08.

Robertson, T., and E. DeCola. (2001). *Joint agency evaluation of the spring and fall 2000 North Slope broken ice exercises.* Prepared for Alaska Department of Environmental Conservation; Minerals Management Service; North Slope Borough, Alaska; U.S. Coast Guard; and Alaska Department of Natural Resources, Anchorage.

Rytkönen, J., J. Sassi, and E. Mykkänen. (2003). *Recent oil recovery test trials with ice in Finland.* 26th Arctic and Marine Oil Spill Program; Technical Seminar June 10-12, 2003.

Schlumberger Oilfield Glossary. (2010). www.glossary.oilfield.slb.com.

Seasonal Ice Zone Observing Network. (No date.). www.sizonet.org.

Shell. (2010). *Chukchi Sea regional exploration oil discharge prevention and contingency plan*. Anchorage, Alaska.

Shigenaka, G., and N. Barnea. (1993). *Questions about in situ burning as an open-water oil spill response technique.* National Oceanic and Atmospheric Administration. HAZMAT Report 93-3. 42 pp.

Short, J.W., *et al.* (Jan. 1, 2004). Estimate of oil persisting on the beaches of Prince William Sound 12 years after the Exxon Valdez oil spill. *Environmental Science and Technology* 38(1):19-25.

Singer, M.M., *et al.* (1998). Effects of dispersant treatment on the acute aquatic toxicity of petroleum hydrocarbons. *Archives of Environmental Contamination and Toxicology*. 34(2):177-187.

Singsaas, I. (2005). *Weathering of oils in open sea and ice-infested waters.* ARCOP Workshop, St. Petersburg, Russia. Oct. 19-20, 2005.

Singsaas, I., and M. Reed. (2006). *Oil spill response in ice-infested waters—need for future developments.* Interspill 2006. London.

SkyTruth. (2010). Gulf oil spill tracker. www.skytruth.org/gulf_oil_spill_tracker.htm.

S.L. Ross Environmental Research Ltd. (1998*). Identification of oils that produce non-buoyant in situ burning residues and methods for their recovery.* American Petroleum Institute and the Texas General Land Office, Washington. 50 pp.

Smith, M.A. 2010. Arctic Marine Synthesis: Atlas of the Chukchi and Beaufort Seas. Audubon Alaska and Oceana: Anchorage.

Smith, W.O., and D.G. Barber (eds.). (2007). *Polynyas: Windows to the world.* Elsevier Oceanography Series 74.

Solsberg, L. (2008). Countermeasures for the Beaufort Transition Season. In: W.F. Davidson *et al.* (eds.), *Oil Spill Response: A Global Perspective.* NATO Science for Peace and Security Series C: Environmental Security. Pp. 91-109.

Sorstrom, S.E., *et al.* (2010). *Joint Industry Program on Oil Contingency for Arctic and Ice-Covered Waters.* Summary Report. SINTEF A14181.

State of Alaska Senate Natural Resources Committee Hearing. (2010). Written testimony of Dr. Jeffrey Short.

Stirling, I. (January 1997). The importance of polynyas, ice edges and leads to marine mammals and birds. *Journal of Marine Systems* 10(1-4):9-21.

U.S. Arctic Research Commission. (2010). *U.S. Arctic Research Commission Recommends Steps to Expanded U.S. Funding for Arctic/Subarctic Oil Research*. White paper final draft. May 26, 2010. http://arctic.gov/publications/usarc_oilspill_5-26-10.pdf.

U.S. Coast Guard. (1998). Safety: We are the enemy. *Safety alert.* www.uscg.mil/hq/g-m/moa/docs/sa0998.html.

U.S. Coast Guard *et al.* (August 2006). *Special Monitoring of Applied Response Technologies.* Seattle.

U.S. Department of the Interior. (May 27, 2010). *Salazar Calls for New Safety Measures for Offshore Oil and Gas Operations; Orders Six Month Moratorium on Deepwater Drilling.* News release. www.doi.gov/news/pressreleases/Salazar-Calls-for-New-Safety-Measures-for-Offshore-Oil-and-Gas-Operations-Orders-Six-Month-Moratorium-on-Deepwater-Drilling.cfm.

U.S. Environmental Protection Agency. (2010). *EPA Response to BP Spill in the Gulf of Mexico*. www.epa.gov/bpspill/dispersants.html.

U.S. Fish and Wildlife Service. (2009). Protection of Pacific Walrus Under the Endangered Species Act May Be Warranted, U.S. Fish and Wildlife Service Finds. News release. www.fws.gov/news/newsreleases/showNews.cfm?newsId=9AB69D79-B55D-6855-C9C8E9E2D5536DB1 Accessed Aug. 11, 2010.

U.S. Fish and Wildlife Service. (2010a). Endangered, Threatened, Proposed, Candidate and Delisted Species in Alaska. Updated May 11, 2010.

U.S. Fish and Wildlife Service. (2010b). *Pacific walrus* (Odobenus rosmarus divergens): *Alaska Stock*. Stock Assessment Review. Revised Jan. 1, 2010. http://alaska.fws.gov/fisheries/mmm/stock/final_pacific_walrus_sar.pdf.

U.S. Geological Survey. (2010). *Walrus tracking and telemetry data acquired from walruses instrumented on the Alaska shores of the Chukchi Sea in September 2009*. Radio-Tagging Field Report. USGS Alaska Science Center, Walrus research project. http://alaska.usgs.gov/science/biology/walrus/pdfs/EC09_Radio_Tagging_Field_Report.pdf.

U.S. Government Accountability Office. (2010). *Additional guidance would help strengthen the Minerals Management Service's assessment of environmental impacts in the North Aleutian Basin*. Offshore oil and gas development. GAO 10-276, Washington.

University of Alaska Fairbanks Geophysical Institute. (2010). 2010 Sea ice break-up forecast for Barrow, Alaska. http://seaice.alaska.edu/gi/observatories/barrow_breakup. Accessed July 31, 2010.

Wadhams, P. (1976). Oil and ice in the Beaufort Sea. *Polar Record*. 18(114):237-250.

Weeks, W.F., and G. Weller. (1984). Offshore oil in the Alaskan Arctic. *Science*. 225(4660):371-378.

Wernham, A. (2007). Inupiat health and proposed Alaskan oil development: Results of the first integrated Health Impact Assessment/Environmental Impact Statement for proposed oil development on Alaska's North Slope. *EcoHealth* 4(4):500-513.

Western Regional Climate Center. (2009a). *Station: Barrow-W Post-Will Rogers Memorial Airport (PABR): Climatological Summary.* July 1996 to December 2008. www.wrcc.dri.edu/summary/brw.ak.html.

Western Regional Climate Center. (2009b). *Station: Wainwright Airport (PAWI): Climatological Summary.* September 1998 to December 2008. www.wrcc.dri.edu/summary/awi.ak.html.

Wilson, D., and D. MacKay. (1987). The behavior of oil in freezing situations. Environment Canada.

Wolfe, M.F., *et al.* (1997). Influence of dispersants on trophic transfer of petroleum hydrocarbons in a marine food chain. *Proceedings of the 20th Arctic and Marine Oil Spill Program Technical Seminar*. Pp. 1215-1226.

World Meteorological Organization. (2005). WMO sea-ice nomenclature. www.aari.nw.ru/gdsidb/xml/nomenclature.asp.

APPENDICES 9

(Photo credit: *John Moran)*

Appendix A: Acronyms and Abbreviations

ACIA	Arctic Climate Impact Assessment
ACS	Alaska Clean Seas
ADEC	Alaska Department of Environmental Conservation
AMAP	Arctic Monitoring and Assessment Program
AMOP	Arctic and Marine Oil Pollution Technical Seminar
APD	Application for Permit to Drill
API	American Petroleum Institute
ARCOP	Arctic Operational Platform
BBO	Billion Barrels of Oil
BCB	Bering, Chukchi and Beaufort Seas population
BOEMRE	Bureau of Ocean Energy Management, Enforcement and Regulation
BOP	Blowout Preventer
BOSS	Behavior of Spilled Oil at Sea
BP	British Petroleum Exploration & Production Inc.
BPXA	British Petroleum Exploration Alaska
COCP	Critical Operations and Curtailment Plan
C-PLAN	Contingency Plan
DOE	Department of Energy
DOI	Department of the Interior
EIS	Environmental Impact Statement
ESI	Environmental Sensitivity Index
FLIR	Forward-Looking Infrared Radar
GAO	Government Accountability Office
GRS	Geographic Response Strategy
IARC	International Arctic Research Center
IEA	Important Ecological Area
JIC	Joint Information Center
JIP	Joint Industry Project
MMS	Minerals Management Service
NEPA	National Environmental Policy Act
NETL	National Energy Technology Laboratory
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NRT	National Response Team
NSIDC	National Snow and Ice Data Center
OCS	Outer Continental Shelf
ODPCP	Oil Discharge Prevention and Contingency Plan

OSB	Ocean Studies Board
OSRB	Oil Spill Response Barge
OSRO	Oil Spill Removal Organization
OSRV	Oil Spill Response Vessel
OST	Oil Spill Tanker
PAH	Polycyclic Aromatic Hydrocarbon
PIC	Person-in-Charge
PPA	Priority Protection Area
PRB	Polar Research Board
PTTEP	PTTEP Australasia Pty Limited
SAC	Science Advisory Council
SERVS	Ship Escort Response Vessel Services
SIZONET	Seasonal Ice Zone Observing Network
SNAME	Society of Naval Architects and Marine Engineers
SWCC	Subsea Well Control and Containment
TAPS	Trans Alaska Pipeline System
TCFG	Trillion Cubic Feet of Gas
UAFGI	University of Alaska Fairbanks Geophysical Institute
USCG	United States Coast Guard
USEIA	United States Energy Information Administration
USFWS	United States Fish and Wildlife Service
USGS	United State Geological Survey
VOC	Volatile Organic Compounds
VOSS	Vessel of Opportunity Skimming System
WMO	World Meteorological Organization
WRCC	Western Regional Climate Center
WSF	Water-Soluble Fractions

Appendix B: Glossary

Benthic: Pertaining to the environment and conditions of organisms living at the water bottom, or benthos.

Bioaccumulation: The concentration of a substance in a living organism, possibly with harmful effects.

Biomagnification: Also known as bioamplification or biological magnification. The increase in concentration of a substance that occurs in a food chain as a consequence of persistence, food chain energy or low rate of internal degradation/excretion of the substance.

Blowout Preventer (BOP): A set of large valves at the top of a well that may be closed if the drilling crew loses control of formation fluids. By closing these valves (usually operated remotely via hydraulic actuators), the drilling crew usually regains control of the reservoir, and procedures can then be initiated to increase the mud density until it is possible to open the BOP and retain pressure control of the formation.

Brash Ice: Accumulations of floating ice made up of fragments not more than 2 meters across; the wreckage of other forms of ice.

Bridge: As in to bridge a well; to seal itself with rock fragments from the collapsing formation.

Broken Ice: An operating environment where a body of water has incomplete coverage of ice. Broken ice varies from less than 10 percent coverage to greater than 90 percent coverage. Mechanical oil spill recovery effectiveness is diminished at ice concentrations greater than 10 percent and generally precluded at concentrations above 70 percent.

Calm Water: An operating environment where the sea state is usually less than 1 foot waves and currents are less than 0.8 knots; includes waters that are very sheltered from wind and waves or very small bodies of water. This is the least demanding operating environment for waterborne oil spills.

Candidate Species: A species for which the U.S. Fish and Wildlife Service has on file sufficient information on biological vulnerability and threat(s) to support proposals as threatened or endangered (under the Endangered Species Act).

Copepods: Small, shrimplike animal of the subphylum *Crustacea* (includes crabs and lobsters) that are only a few millimeters in diameter and are called zooplankton—or animals that float in the sea. They eat microscopic algae called phytoplankton. They are an important part of the food chain because they are typically eaten by fish.

Decant: To remove free-water from an oil-water mixture by drawing the water off the bottom of the oil-water interface.

Dispersant: A chemical formulation containing surface active agents (surfactants) that lowers the surface tension between oil and water and facilitates the breakup and dispersion of oil into the water column in the form of finely divided droplets to allow for natural biodegradation.

Downhole: Farther into a well bore, rather than at the Earth's surface.

Drilling Fluids: Any of a number of liquid and gaseous fluids and mixtures of fluids and solids (as solid suspensions, mixtures and emulsions of liquids, gases and solids) used in operations to drill bore holes into the Earth. Also known as drilling mud.

Emulsification: A process by which oil forms an emulsion or "mousse" consisting of many small droplets of water incorporated into the oil.

Encapsulation: The absorption of a polymer film onto cuttings and well-bore walls to form a coat or barrier.

Endangered Species: One that is in danger of extinction throughout all or a significant portion of its range.

Entrain: To incorporate with and carry along.

Entrainment: The loss of oil from containment when it is pulled under a boom by a strong current; typically occurs when booms are deployed perpendicular to currents greater than 1 knot (0.5 meter [almost 20 inches] per second).

Fast Ice: Sea ice that forms and remains fast along the coast, where it is attached to the shore, an ice wall or an ice front, or between shoals or grounded icebergs.

Federal Waters: Marine waters of the outer continental shelf from the three-mile state waters boundary to the border of the U.S. exclusive economic zone, 200 miles from the contiguous shoreline.

Floe: Any relatively flat piece of sea ice 20 meters (22 yards) or more across.

Frazil Ice: Fine spicules or plates of ice, suspended in water.

Geographic Response Strategies (GRSs): Site-specific spill-response methods used to protect sensitive coastal environments from the deleterious effects of petroleum or other hazardous-substance spills. GRSs provide first responders with specific guidance for a rapid deployment of pre-identified actions to protect priority sensitive sites.

Grease Ice: When crystals have coagulated to form a soupy layer on the surface; a later stage of freezing than frazil ice.

Haul-Outs: Locations on land or ice where marine mammals such as walrus and seals climb out of the water to rest or nurse their young.

Ice Gouging or Ice Scour: The abrasion of material in contact with moving ice in a sea, ocean or other body of water.

Ice Rubble: Fragments of floating ice, 1 to 5 feet high, frozen in water.

Lead: Any fracture or passageway through sea ice that is navigable by surface vessels.

Nearshore: A shallow-water operating environment close to the coast.

Open Water: An operating environment where the sea state can reach 6 feet and moderate waves and whitecaps may occur. Includes open water that is not sheltered from wind and waves. This is the most demanding operating environment for waterborne spills.

Pack Ice: In a wide sense, includes any area of sea ice other than fast ice no matter what its form or how it is disposed.

Pancake Ice: Predominantly circular pieces of ice from 30 centimeters to 3 meters (1 foot to 10 feet) in diameter and up to about 10 centimeters (4 inches) thick, with raised rims due to the pieces striking against one another.

Phytoplankton: Microscopic marine plant, or algae that floats in the ocean. They convert carbon dioxide and sunlight for energy and release oxygen as a waste product. They are at the base of the marine food web. In the Arctic food web, they play a very important role as they grow on the underside of the ice as in the spring and are a source of food for zooplankton such as amphipods.

Polynya: An area of open water surrounded by sea ice.

Protected Water: An operating environment where the sea state can reach 3 feet and small waves and whitecaps may occur. Protected waters have limited shelter from wind and waves. Protected water falls between open water and calm water in the classification scheme.

Recolonization: The process of a new community of plants and animals coming to inhabit a space after a disturbance has displaced most of the flora and fauna.

Sea Ice: Any form of ice found at sea that has originated from the freezing of seawater.

Sea State: A sea state is the general condition of the free surface on a large body of water—with respect to wind waves and swell—at a certain location and moment. A sea state is characterized by statistics, including the wave height, period and power spectrum.

Secondary Containment: Structures, usually dikes or berms, surrounding tanks or other storage containers and designed to catch material spilled from the storage containers.

Sessile: A plant or animal that is not able to move freely because it is permanently attached to the substrate, such as a rock. Examples of sessile marine plants include algae and such marine animals as barnacles and coral.

Slush Ice: Snow that is saturated and mixed with water on land or ice surfaces, or as a viscous floating mass in water after a heavy snowfall.

Solid Ice: Where a body of water has complete coverage of ice. Spill response activities may occur on solid ice only after it is determined that the ice is of sufficient thickness to safely support response personnel and equipment.

Staging Area: Location where incident personnel and equipment are available for tactical deployment. Can serve as a check-in location for equipment and personnel reporting to the incident.

State Waters: Marine waters out to three miles from the contiguous shoreline, over which the state has jurisdiction.

Substrata: The area upon which an organism, such as a clam or barnacle, is attached. It can also be a layer of rock or soil immediately beneath the surface of the Earth.

Task Force: A group of resources with common communications and a leader assembled for a specific mission. Often used in oil spill response planning and management.

Threatened Species: One that is likely to become endangered within the foreseeable future throughout all or a significant portion of its range.

Trophic Level: Trophic levels define the position of an organism in a food web or chain. Trophic is a Greek word that means feeding. The first level of a food chain contains the primary producers, which are generally the plants and algae that produce their own energy using light and carbon dioxide. Animals that eat plants are at the next level, while predators are at the third level.

Wave Period: The average amount of time between passages of successive crests (or troughs) of waves.

Weathering: The chemical and physical changes that occur once oil has spilled, including spreading, evaporation, dissolution, photooxidation, dispersion, biodegradation and emulsification.

Well Bay: An area of an oil platform where the wellheads are located. It normally consists of two levels, including a lower level where the wellheads are accessed, often along with the various well control panels, which will have pressure gauges and controls for hydraulically actuated valves, including downhole safety valve and annular safety valve.

Well bore: A hole created by drilling.

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