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Offshore Oil Spill Response in Dynamic Ice Conditions

A Report to WWF on Considerations for the Sakhalin II Project

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Authors: Elise DeCola, Tim Robertson, Sierra Fletcher, Nuka Research and Planning Group, LLC; Susan Harvey, Harvey Consulting, LLC

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Cover photo: Alaska Department of Environmental Conservation, North Slope Broken Ice Drills, 2000

About the Authors

This report was prepared for WWF by Elise DeCola, Tim Robertson, and Sierra Fletcher, Nuka Research and Planning Group, LLC, and by Susan Harvey, Harvey Consulting, LLC.

Elise DeCola has published extensively in the field of oil spill prevention and response. She began her career as a policy analyst in the Rhode Island Senate, where she researched and developed legislation to strengthen oil spill prevention requirements for oil-laden vessels. For the past decade, she has actively participated in oil spill planning projects throughout the US, with a focus in Alaska. She has developed and reviewed oil spill contingency plans and emergency operations manuals for production platforms, storage facilities and pipelines in Alaska, the Gulf of Mexico, and West Africa. Ms. DeCola has participated in the design, execution, and critique of dozens of oil spill drills, exercises, equipment trials, and training programs, including the 2000 Beaufort Sea equipment trials. Ms. DeCola holds BS in Environmental Science and an MA in Marine Affairs.

Tim Robertson began his career as a research biologist with the Alaska Department of Fish and Game. He spent nine years working in environmental compliance and drilling operations in Alaska, including six drilling projects in the offshore Beaufort Sea, and five drilling projects in Cook Inlet. He has been active in oil spill response and prevention planning since the 1989 Exxon Valdez oil spill, when Mr. Robertson served as the Director of Operations for Seldovia, Alaska. In the years since, he has filled numerous positions in oil spill incident management teams in Alaska, and has firsthand experience operating oil spill response equipment in open water and dynamic ice environments. From 1989 to 1991, he served as a founding director and Vice-President for Oil Spill Prevention and Response for the Prince William Sound Regional Citizens' Advisory Council. As a representative of the Council, Mr. Robertson was a delegate to the Negotiated Rulemaking Committee to develop the implementing regulations for the US Oil Pollution Act of 1990. He holds a BS in Fisheries Biology and a MS in Fisheries Science.

Susan Harvey is a Petroleum Engineer with extensive experience working on the Alaska North Slope. From 1987-1999, she held engineering and supervisory positions with British Petroleum Exploration Alaska, Standard Oil, and Arco. She later worked as a regulator for the Alaska Department of Environmental Conservation, as the Industry Preparedness and Pipeline Program Manager for the Division of Spill Prevention and Response. In that position, she oversaw contingency planning and compliance programs for all of Alaska, including operations in the Alaska North Slope and Beaufort Sea. She now works as a private consultant and is an adjunct professor of environmental engineering at the University of Alaska Anchorage. She holds a BS in Petroleum Engineering and an MS in Environmental Engineering.

Sierra Fletcher does research, writing, and facilitation work in the environmental and conflict resolution fields. She has worked on projects in the US, Cambodia, Middle East, Afghanistan, India, and Pakistan. Her experience includes designing and facilitating workshop and consensus-building opportunities for both youth and adults; researching and advising on energy and environmental issues; and writing proposals and reports for the projects of US government agencies, multilateral institutions, and private foundations. Ms. Fletcher has a B.A. from Yale University in Anthropology, and a Master's in Law and Diplomacy from the Fletcher School at Tufts University.

Contents

Executive Summary

Concerned about a major oil spill from the Sakhalin II 0il and Gas Project (Sakhalin II) under development by the Sakhalin Energy Investment Company (SEIC) in the Russian Far East, WWF (the World Wide Fund for Nature) commissioned a study of the current state-of-technology for offshore oil spill response under dynamic sea ice conditions.

WWF is particularly concerned about the potential impact of an oil discharge from Sakhalin II on the Western North Pacific gray whale population. The entire population of this endangered gray whale sub-species migrates every summer to feed on bottom-dwelling organisms in the waters off Sakhalin Island. Roughly 100 remaining individuals (ISRP 2005) are vulnerable to potential spills from increasing oil and gas developments in close proximity to their feeding grounds. Prevention of spills and effective response to a major oil spill in the marine waters around Sakhalin Island may be critical to this species' survival.

Marine waters around Sakhalin Island are partially or completely covered with sea ice from November until May each year. Ice conditions are highly variable and heavily influenced by seasonal, diurnal, and weather-driven temperature, winds, and sea states. The dynamic ice conditions in the Sea of Okhotsk are dominated by periods of drift ice, at times including areas of contiguous pack ice. Because of the nature of this constantly changing ice regime, oil spilled in this environment would be difficult to contain, track, and recover.

This report explores the current state-of-technology for the three primary oil spill response methods: (1) mechanical recovery, (2) dispersants, and (3) in-situ burning and considers their potential use at the Sakhalin II project during broken ice conditions. This report concludes a "dynamic ice response gap" exists for Sakhalin II operations, due to well-documented limitations on the effectiveness of oil spill response technologies when sea ice is present. Other environmental factors, such as sea state, visibility, current, and temperature, contribute to these limits.

Initial planning documents for Sakhalin II propose oil and gas operations to be conducted year round, including periods when significant dynamic drift ice is present in the Sea of Okhotsk. Potential spill sources include the offshore platform tanks, piping and wells, subsea pipelines, marine terminal, and tanker operations. Oil spills from the proposed Sakhalin II Project have the potential to spill oil on ice, under the ice, or interspersed with broken ice. Available oil spill response technologies are limited by the prevailing ice conditions at Sakhalin, which are characterized by constantly shifting ice formations that range in coverage from 20% to 80% and are rarely stable enough to support on-ice spill response.

Mechanical recovery is extremely difficult in ice-infested waters, and is not an effective response option for large scale oil spills above 30% ice coverage. Dispersants are an unproven technology in ice-infested waters. There is considerable technical debate among experts about the efficacy of in-situ burning as a primary oil spill response tool in the arctic, particularly under dynamic ice conditions. A review of published literature reveals that in-situ burning has not been demonstrated in actual field tests to be effective in ice coverage above 30% or below 70%. Above 70% coverage, sea ice may provide natural containment, although the sea ice may transport oil great distances so that it is unavailable for response once spring break up occurs. At higher ice concentrations, significant logistical, technical, and safety challenges remain in tracking, accessing, and igniting the oil slicks and recovering burn residues.

Similarly, while in-situ burning may be a response option to ignite well blowouts, it has not been demonstrated effective for cleaning up oil from well blowouts in the arctic. Oil well blowouts spray oil long distances away from the source, creating a thin, dispersed oil slick with depleted volatile components, which may be impossible to ignite in open water, broken ice conditions, or due to environmental conditions on-scene.

Oil spilled in ice-infested waters, and especially under the ice layer, is not only difficult to contain, it is very difficult to track and model. Marine oil spill tracking and remote sensing technology generally relies on air operations, which can be severely constrained by environmental and logistical factors in winter. Existing mathematical models cannot accurately predict the movement of oil on, under, or among offshore ice, although this is an area where considerable research and development is ongoing.

Research and development projects continue to focus on technologies and methods to improve oil spill response in ice-infested waters, and several new technologies for mechanical recovery in ice-infested waters have been introduced. However, the challenge lies in applying these technologies at the scale necessary to clean up a major oil spill.

The limits to oil spill response technologies in ice-infested waters create a "response gap." This report describes the factors that contribute to the dynamic ice response gap for arctic offshore oil and gas developments such as Sakhalin II. Environmental factors, such as wind speed, sea state, visibility, safety considerations, and logistics contribute to the response gap by further narrowing the window of opportunity to contain, control, and recover oil spilled to marine waters off Sakhalin Island during the ice season.

This report does not attempt to quantify the response gap at Sakhalin II; however, additional study of this topic is recommended. Quantification of the specific nature of the Sakhalin II response gap would require detailed analysis of the environmental and ice conditions at the project location and a consideration of the specific spill response technologies that will be used there. Such calculation would provide an extremely useful planning tool, shedding additional light on the number of days a year when ice conditions, wind, sea state, visibility, or cold temperatures may render oil spill response operations unsafe or ineffective. An understanding of the response gap provides additional perspective on the potential oil spill risks and impacts from the project.

This report recommends further analysis of the response gap created by environmental conditions in the Sea of Okhotsk, including but not limited to sea ice. Additional research is recommended to better understand the potential environmental and wildlife consequences of an oil spill from Sakhalin II. These include: further study of the impacts of sunken in-situ burn residues to whales that feed on benthic organisms; calculation of worst case oil well blowout volumes based on the open orifice flow rates for the reservoirs; additional analysis of the risks from tanker operations at the oil and LNG export terminal; development of site-specific trajectory models that predicts how oil from various Sakhalin spill scenarios might impact gray whale feeding areas; and additional studies regarding the physical and chemical behaviour of Sakhalin crude oils in ice-infested waters.

Further analysis of the Sakhalin II response gap and associated issues will aid in developing oil spill prevention measures and risk mitigation strategies. Spill prevention and risk mitigation policies have been successfully implemented at other oil and gas production operations, including: enhanced leak detection systems, redundant prevention systems, double-hulled and ice breaking vessels, scheduling higher risk operations when effective response is possible, and avoiding higher risk operations during the broken ice period when an oil spill response will not be effective.

"Oil spilled in broken-ice cannot be cleaned up effectively, and it is expected that whales would not avoid oil-fouled waters." (NRC 2003b)

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

"If oil is widely distributed throughout broken ice, no countermeasure methods might be practical." (Owens *et al.* 1998)

"Adverse weather conditions sometimes preclude any response at all and require a 'wait until thaw' approach." (Oskins and Bradley 2005)

"No current cleanup methods remove more than a small fraction of oil spilled in marine waters, especially in the presence of broken ice." (NRC 2003b)

"In some cases, safety concerns will necessitate the 'monitor and wait' approach rather than attempting a risky marine operation, which might also have a very limited chance of success." (Dickins 2005)

Spill response experts agree that existing oil spill response technologies cannot effectively clean up a large scale oil spill to ice-infested waters, and considerable research is ongoing to improve these technologies. However, until more effective clean up methods are realized, the oil spill response gap in ice-infested waters must be considered in developing oil spill contingency plans and spill prevention measures for oil and gas developments where dynamic ice conditions exist.

The oil spill response gap in ice-infested waters amplifies the potential impacts of an oil spill from Sakhalin II to the critically endangered gray whale. One study estimates the risk of a major pipeline release at 24% over the lifetime of a project, and a blowout at 3% (ISRP 2005). If a major well blowout, pipeline release, or tanker spill occurred during the six months of the year when broken ice conditions prevail, an effective cleanup is unlikely. Unrecovered oil would persist in the marine environment, with the potential to pollute the water column, shoreline, and sea bottom, and contaminate the Western North Pacific gray whale feeding grounds. Contamination could linger for years, causing irreparable cumulative damage to an extremely vulnerable sub-species.

1. Introduction

1.1 Purpose and Scope

The purpose of this report is to investigate the current state-of-technology for offshore oil spill response under dynamic, offshore broken ice conditions. In response to the potential for a major oil spill from the Sakhalin II 0il and Gas Project (Sakhalin II) proposed by the Sakhalin Energy Investment Company (SEIC) in the Russian Far East in the Sea of Okhotsk, the World Wide Fund for Nature (WWF) commissioned a study to investigate the current state-of-technology that exists for offshore oil spill response under dynamic sea ice conditions. WWF is particularly concerned about the possibility that spilled oil would persist in the environment and threaten the summer feeding grounds of the critically endangered Western North Pacific gray whales (WGW).

This report considers the technological, operational, and logistical challenges associated with mounting an oil spill response in sea ice conditions, in order to better understand the potential environmental impacts from a major oil spill from Sakhalin II, and the possibility for spilled oil to persist in the nearshore environment and threaten the summer feeding grounds of the WGW.

This report examines the state-of-technology for oil spill response operations in dynamic, broken ice conditions by compiling and analysing published articles, technical reports, peer-reviewed studies, and drills and exercise reports where ice conditions were present. Further information was gathered through interviews with recognised experts in the field of arctic spill response and the authors' firsthand experience observing oil spill response operations, exercises, and equipment trials. Information gathered through the literature review, interviews, and our own experience has been combined to draw conclusions regarding the limits to existing, proven technologies' ability to track, contain, control, and recover oil spills in dynamic ice conditions. Since dynamic broken ice conditions are predominant in the offshore Sakhalin Island environment, the challenges of oil spill response under these conditions are a focus of this report.

This report also describes what is known about the fate and effect of crude oil spilled in broken ice and the potential exposure pathways for benthic-feeding marine mammals, including the WGW.

An expedited peer review was conducted prior to the release of this report.

1.2 Organization of Report

This report is organized into five sections.

Section 1 contains introductory information, including an overview of the proposed Sakhalin II oil and gas operations and a description of the WGW summer feeding activities in the region.

Section 2 provides a brief overview of the fate and effect of oil spilled to ice-infested waters and describes the physical characteristics of sea ice and the dynamics of sea ice formation and movement. This section examines the challenge of predicting oil spill behaviour in sea ice, using tools such as oil spill trajectory modelling. Section 2 also evaluates the long-term fate of oil spilled in the arctic marine environment, including the potential exposure pathways for benthic-feeding whales and other marine mammals.

Section 3 summarizes the state-of-technology for commercially available oil spill response technologies that may be capable of recovering oil spilled in ice-infested marine waters. Both mechanical and non-mechanical response tactics and equipment are evaluated.

Section 4 identifies potential obstacles to mounting a safe and effective oil spill response with proven response technologies in a range of sea ice conditions. This section considers the impact of broken ice conditions on the performance of oil spill response techniques and equipment. Technological, operational, and logistical limitations are explored as they relate to the "response gap" for oil spills to a broken ice environment. The response gap discussion considers how limitations to spill response systems in broken ice may impact at-risk resources, specifically the Western North Pacific gray whale.

Section 5 presents the authors' findings regarding documented capabilities and limitations of existing oil spill response technologies in ice-infested waters. The authors recommend a combination of best practices for spill response in ice-infested waters using available technologies, emphasizing the importance of spill prevention measures to reduce or eliminate oil spill risk when ice conditions preclude the ability to mount a safe and effective oil spill response.

1.3 Overview of Sakhalin II Project

As part of Phase 2 of the Sakhalin II Project located northeast of Sakhalin Island, SEIC has proposed to expand production of oil, and begin production of gas, from two new offshore platforms. SEIC is leading this project under a Production Sharing Agreement (PSA) between the Russian Federation Government, the Sakhalin Oblast Administration and Sakhalin Energy. SEIC is a company established for implementation and development of the Sakhalin II Fields. The current shareholders are Shell Sakhalin Holdings B.V. (Shell), which has a 55% share in the project, Mitsui Sakhalin Holdings B.V. (Mitsui) which has a 25% share and Diamond Gas Sakhalin, a Mitsubishi company, with a 20% share.

Sakhalin II includes two development license areas offshore of the northeast of Sakhalin Island: Piltun-Astokhskoye and Lunskoye. The Piltun-Astokhskoye license area is predominantly oil, and the Lunskoye license area is predominantly gas. Together these oil and gas fields contain approximately 600 million tonnes of crude oil and 700 billion cubic metres of gas (SEIC 2005b).

1.3.1 Phase 1

Phase 1 of Sakhalin II began oil production in 1999 from a single platform in the Piltun-Astokhskoye field. The Phase 1 facility is located 16 km to the Northeast of Sakhalin Island, in about 30 m of water. The Molikpaq platform, a mobile caisson drilling unit, was installed in September 1998 and is capable of drilling and producing from up to 32 wells (ABS 2001). A production facility complex called the Vityaz was built around the Molikpaq platform to process hydrocarbons. (SEIC 2005b). A Floating Storage Offloading (FSO) unit called the Okha is connected to the facility by a Single Anchorage Leg Mooring (SALM) buoy and a 2 km subsea pipeline which is used to transfer oil from the facility to tank vessels (ABS 2001). Oil flows through the subsea pipeline to the SALM riser piping and swivel and then passes through a submerged flexible loading hose to the bow of the FSO. Oil is then loaded onto a marine tanker and is transported to market. Oil production from the Phase 1 platform is limited to approximately 180 days per year because the facility encounters dynamic ice conditions approximately half the year, and marine tankers are not able to safely load or transport oil to and from the platform in dynamic ice conditions. Peak production from the Phase 1 facility will reach 90,000 barrels of oil. (SEIC 2005b).

1.3.2 Phase 2

In Phase 2 of the Sakhalin II Project, SEIC proposes to add two more offshore platforms: one to expand oil development in the Piltun-Astokhskoye oil field and a second one to commence gas development from the Lunskoye gas field. The two new Phase 2 drilling platforms are being built in Russia, and will have concrete gravity base structures to withstand ice conditions in that area (SEIC 2005b).

Phase 2 is being developed to enable year-round oil and gas production by connecting all three platforms (Phase 1 and Phase 2) to an onshore processing unit on Sakhalin Island by a 165 km subsea pipeline system. Oil from the Piltun-Astokhskoye field will be transported overland through an 800 km pipeline to the southern tip of Sakhalin Island, to an oil export shipping terminal that will be accessible year-round (Figure 1-1). Hydrocarbons produced from the Lunskoye natural gas field will be processed at an onshore processing facility to separate out the gas and condensate. The gas and condensate will be transported overland though an 800 km pipeline to the southern tip of Sakhalin Island, to Russia's first liquid natural gas (LNG) plant (Figure 1-1). Both the LNG plant and the

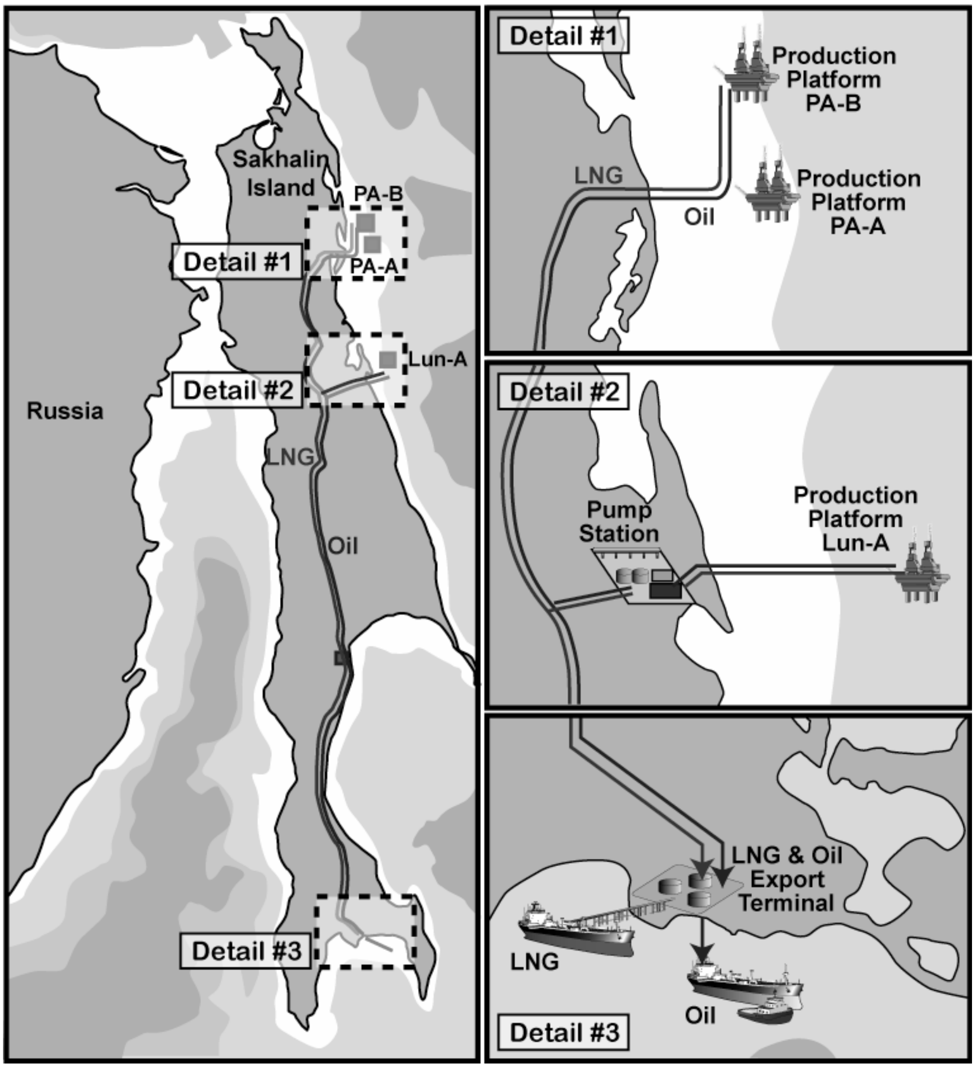


Figure 1-1: Overview of Sakhalin II

oil export terminal will be built on a 200-hectare site at Prigorodnoye on Aniva Bay 15 km east of Kosakov. The LNG plant will have an annual production capacity of 9.6 million tonnes. The oil export terminal will be located 500 m east of the LNG facility. Oil will be exported through a 4.5 km sub-sea pipeline and from a tanker loading unit located offshore in Aniva Bay (SEIC 2005b).

1.3.3 Oil Spills at Sakhalin II

There are several ways hydrocarbons could be released from existing and proposed Sakhalin II operations: blowout while drilling an oil well, failure of a production well's safety system, transportation pipeline leaks, facility piping leaks, storage tank leaks, marine terminal releases, or vessel discharges.

Blowout while drilling an oil well. An uncontrolled oil well blowout poses the largest risk of a catastrophic oil spill, assuming the oil reservoir pressure is sufficient to flow to the surface. This is especially so during exploratory operations where subsurface reservoir pressures are not well known.

While drilling an oil well, the subsurface pressure is controlled using drilling muds placed in the wellbore. Based on the subsurface pressure expected for the oil and gas reservoir, drilling engineers design drilling mud systems with sufficient density to control the subsurface pressure; however, it is not always possible to predict the exact magnitude of the subsurface pressure that will be encountered, especially when drilling an exploration well into a previously unexplored area. If the subsurface pressure exceeds the weight imposed by the column of drilling mud in the wellbore, the reservoir formation fluids (e.g. oil and gas) will flow into the wellbore and will eventually flow to the surface of the well causing pressure to build at the wellhead. To prevent drilling mud and associated hydrocarbons from being released into the environment, drilling rigs are equipped with a blowout preventor (BOP) system consisting of heavy duty valve assemblies at the wellhead and metal casing cemented into the wellbore to control well pressure. Properly designed blowout prevention systems should control excess pressure at the wellhead; however, under-designed or malfunctioning systems may fail to contain the excess pressure resulting in a release of drilling mud and hydrocarbons.

An oil well blowout may occur at the surface, causing oil to be deposited on the water, sea ice, platform, or other adjacent features. A subsea oil well blowout may result in an underwater release, with the oil and gas rising through the water column and to the ocean surface. When sea ice is present, oil may collect below the ice or between ice floes.

An uncontrolled oil well blowout poses the largest catastrophic oil spill risk, as the entire volume of the reservoir could be released unless the well is controlled. Though infrequent, blowouts can last for days or weeks until well control is finally achieved. A well can be controlled in three ways: it "bridges" on its own by plugging with sand or debris; human or mechanical intervention such as well capping, drilling a relief well, or well ignition is effective; or the reservoir pressure drops enough that the BOP system or drilling mud starts working again.

Proper design of the drilling mud and BOP system is critical to reduce the risk of a blowout. The inability to accurately predict exploration well pressure requires that mud systems and blowout prevention systems be designed with an adequate safety factor to ensure unexpected pressures can be controlled while drilling. Due to the higher risk of exploratory drilling, it is prudent to schedule these drilling operations during seasons in which oil spill response is possible and during periods of the lowest environmental impact.

One study estimates the risk of a well blowout from Sakhalin II at 3% over the lifetime of the project (ISRP 2005).

Well safety system failure. Once an oil well has been drilled it must be "completed" so it can be placed into production. Metal casing is placed into the wellbore and is cemented in place to stabilize the reservoir, prevent collapse, and control pressure. Inside the casing, a series of valves and piping controls the well pressure and provides a conduit for hydrocarbons to flow to the surface.

Offshore production wells are often equipped with emergency shutoff valves in the wellbore (sub-surface safety valves); these valves close in a fail-safe position when excessive pressure is encountered in the wellbore. 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. The surface safety valve is designed to close if excessive pressure is observed at the wellhead, or if a surface leak occurs causing a sudden drop in pressure.

The risk of a production well oil spill increases with the age of the equipment and the corrosive and erosive nature of the hydrocarbons produced. Valves and piping subject to corrosive fluids or erosion may fail to prevent hydrocarbons from reaching the environment. Routine maintenance, inspection, repair and replacement programs are critical oil spill prevention measures to reduce the risk of these types of spills. As production operations mature, there may also be a tendency toward complacency, which can contribute to the risk of a production well spill.

Transportation pipeline leaks. Oil may be transported from production platforms to onshore facilities through subsea pipelines, as proposed for Sakhalin II. The potential oil spill volume from a pipeline release is directly related to how much oil is in the pipeline and how fast it is moving. The worst case spill from a transportation pipeline is usually considered to be a breach that allows all the oil in the pipeline to escape rapidly. However, a slow and steady leak that goes undetected could be worse. Significant volumes of oil can be released in an undetected spill, as happened on Alaska's North Slope in March 2006, resulting in the largest spill from oil and gas operations there to date. Approximately 760,000 litres of Prudhoe Bay crude oil was released to the environment (ADEC 2006).

The actual volume and rate of oil released from a pipeline will be constrained by the seabed floor topography and the hydrostatic column above the pipeline. Typically, offshore pipelines are designed with shut-off valves at both the platform and shore ends. If a leak is detected in the marine pipeline system by the pipeline leak detection system or human observation, the pipeline can be shut down to prevent further oil from flowing through the oil line. Once the pipeline valves are shut in, the potential spill volume is limited to the oil already in the pipeline.

A properly designed pipeline and leak detection system capable of detecting even the smallest chronic leaks is a critical component of the oil spill prevention strategy for subsea pipelines. International oil companies, working with expert leak detection vendors, have developed leak detection technology claimed to detect extremely small leaks. For example, a subsea pipeline constructed in the Beaufort Sea by BP for its Northstar oil field included redundant leak detection systems capable of meeting a leak detection standard of approximately 0.05% of the peak crude oil flow rate. Several other available leak detection systems are reportedly capable of detecting leaks of between 0.1% and 0.5% (AGOC 2000, ATMOS 2002, EFA 2002). Quality control procedures, equipment testing, and monitoring programs are essential to ensure the long-term effectiveness of such systems.

A release from a subsea pipeline would be similar to a subsea blowout in that, when ice is present, the oil will collect underneath the ice or pool in between the ice floes. A pipeline release that occurs at or above the waterline would discharge oil to the sea surface.

To prevent leaks, a pipeline must be designed with materials appropriate to the environment and expected length of service. Compared to pipelines on land, offshore pipelines are characterized by their faster corrosion from saltwater exposure, greater potential to harm a fragile marine environment, and inaccessibility during most of the year due to water and ice. They are inherently more difficult to inspect and repair.

Spill prevention options for offshore pipelines in cold climates include: double-walled pipes, subsea utility corridors encasing multiple pipelines in a conductor pipe, and specialized arctic piping design. State-of-the-art, redundant leak detection systems should be installed, with the capability to monitor variations in pressure, temperature, flow rate, and hydrocarbon vapour releases. In some cases it is necessary to bury the pipeline well below the seabed or protect it with a thick cement casing to avoid ice gouging. Pipelines must be protected from internal and external corrosion and erosive forces, and should undergo routine maintenance, inspection, repair, and replacement programs to ensure pipeline integrity.

One study estimates the risk of a major pipeline release from Sakhalin II at 24% over the lifetime of a project (ISRP 2005).

Storage tank and facility piping leaks. Offshore drilling operations involve extensive networks of tanks and piping. Oil may be spilled from the storage tanks on or off shore, facility piping, platform valves, or the export terminal. Oil spilled from onshore piping or tanks may travel to streams, wetlands, or coastline areas. 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 the volume and effectiveness of the secondary containment around the tanks and piping and how quickly the leak is controlled. Unlike onshore facilities, offshore platforms often are not equipped with secondary containment structures built to contain 100% of storage tank and facility piping leaks. Offshore platform storage tanks are sometimes located in the platform structure and the pipelines not contained, so a spill would leak directly to water.

Improvements in offshore oil spill prevention systems for 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.

Marine terminal releases. Hydrocarbon spills may occur at marine terminals which transport oil or LNG. Hydrocarbons may be released from tanks and piping at the terminal, and may be discharged directly into the ocean from leaks at the marine header as the vessel is loaded. Spill prevention measures for marine terminals storing and transporting oil are described above.

LNG facilities pose an additional spill risk due to explosion. In its liquid state, LNG is not explosive. For an explosion to occur, LNG must vaporise and mix with air in the proper proportions (5% to 15%), and be exposed to an ignition source. In January 2004, there was a major explosion at the Sonatrach LNG liquefaction facility in Skikda, Algeria. To date, there have been no major hydrocarbon spills from an LNG terminal.

Vessels discharges. Oil and LNG tankers exporting hydrocarbons from the facility present a spill risk both during oil transfer operations and in transit. The potential spill volume from a laden tanker ranges from a small spill during oil transfer to a catastrophic cargo loss. Vessel spills pose an additional response challenge because they can occur virtually anywhere along the vessel route. A vessel spill may release hydrocarbons above or below the sea surface, depending upon where the tank is breached.

Spill prevention measures for tank vessels may include: double hulls or double bottoms; leak detection systems; vessel traffic systems; ice detection monitoring systems; weather monitoring systems; navigational restrictions during periods of adverse weather; personnel training; drug and alcohol testing; medical monitoring; and watch standing procedures that ensure adequate crew rest. Human factors – human or organizational errors – have been cited as the cause for approximately 85% of marine vessel accidents; therefore, programs that improve human performance are critical to preventing vessel-source oil spills (USCG 1998).

As required by Russian and international law, and according to the criteria of shareholders and lenders, SEIC is developing an oil spill response plan for Phase 2 operations. An oil spill response plan (OSRP) exists for Phase 1 operations in the Piltun-Astokhskoye Permit Area (SEIC 2004); however, the Phase 2 OSRP was not available to the authors for review at the time of publication. Preliminary SEIC Phase 2 documents propose in-situ burning of spilled oil as a primary response tactic, in lieu of mechanical response methods which are likely to be limited by sea ice conditions. Mechanical recovery would still be used, where possible. SEIC has indicated that mechanical recovery is the only response option that will be allowed in the Piltun feeding area (SEIC 2004, SEIC 2005, WGW Workshop Report 2005).

1.4 Western North Pacific Gray Whales (WGW)

The Western North Pacific gray whale (*Eschrichtius robustus),* a genetically and geographically distinct sub-species, migrates annually to summer feeding grounds off northeast Sakhalin Island. This population has been designated as “critically endangered” by the IUCN-World Conservation Union, and is on the endangered species lists for both the United States (US) and Russia. The worldwide WGW population is estimated at just over 100 whales, of which as few as 23 females may be reproductively active. In recent years, up to half the population that has been observed summering in the vicinity of the Piltun-Astokhskoye field were underweight, for unknown reasons. The same phenomenon has been observed among Eastern Pacific gray whales.

The Sakhalin II project is located near the only known feeding ground for the WGW, which arrives from an unknown wintering area when the ice in Northeast Sakhalin subsides (as early as May) and leaves by the time freeze-up begins in November (Figure 1-2). The nearshore feeding grounds and related whale activity are in the same area as the Piltun-Astokhskoye field, where one platform is already operational (Phase 1 of

Sakhalin II) and another is under construction (the first of two platforms under construction for Phase 2 of Sakhalin II). According to SEIC-sponsored monitoring programs, the whales most likely pass the Lunskoye field, where a third platform is under construction, as they migrate along their coastal route. The WGW feed in nearshore areas up to 40 m deep, which includes the depth at which the platforms are located (SEIC 2005). Scat analysis shows the whales eat benthic and epibenthic invertebrates and plankton primarily from nearshore areas (Gerzig *et al.* in ISRP 2005).

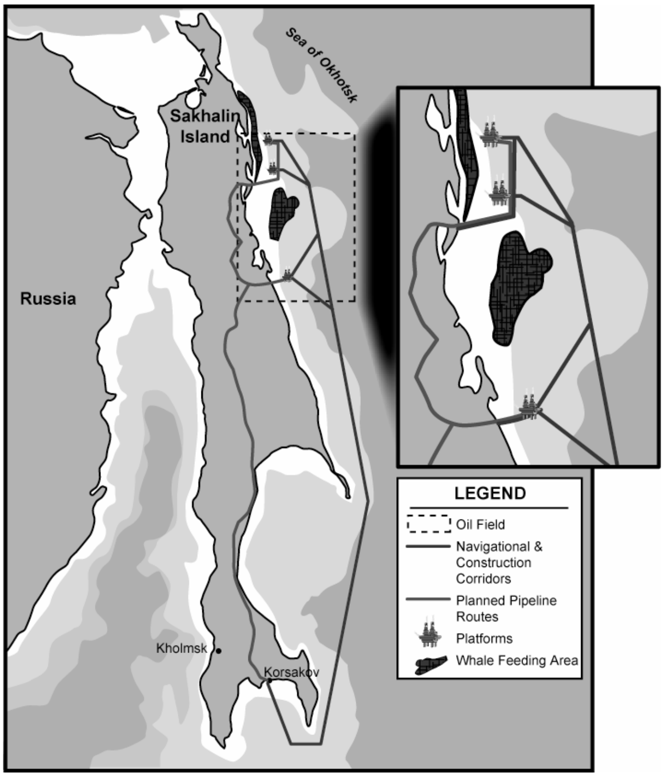


Figure 1-2. Western North Pacific gray whale feeding areas in vicinity of Sakhalin II

Oil and gas development off Sakhalin Island could impact these whales or other species in several ways: disruption of activities due to noise; presence of and collisions with vessels and equipment; seismic surveys; dredging or other impacts to the habitat of prey; and toxic contamination of the feeding area and therefore the food supply (SEIC 2005).

This report considers the potential for an oil spill from Sakhalin II, Phase 2 to persist in the environment and impact the long term survival of the WGW. The focus of this report is on the limits to oil spill response technologies in ice-infested waters. A more detailed discussion of potential impacts of oil spills and oil and gas development to WGW is presented in the Independent Scientific Review Panel (ISRP) report entitled *Impacts of Sakhalin II phase 2 on Western North Pacific gray whales and related biodiversity*.

2. Fate and Effect of Oil Spilled to Ice-covered Waters

2.1 Sea Ice Conditions

Sea ice is characterized by its variability based on air and water temperature, salinity, tides and currents, precipitation, and water depth (AMAP 1998).

Although always in transition from one form to another due to seasonal and diurnal changes in temperature, weather, and tide, it is useful to look at the basic forms of ice in high latitude marine environments to better understand how they may affect oil spill response. Numerous terms have been developed for different forms of ice and snow; those listed here reflect the general terminology used in oil spill response literature, and are based on a glossary of sea ice terminology from the World Meteorological Organization (WMO).

Ice regimes for specific locations are difficult to predict. Even in one locale, the conditions and resulting sea ice formations may vary from year to year, as they do around Sakhalin (Dickins 2005). This section describes typical ice formations and summarizes general considerations for spill response operations.

2.1.1 Fast Ice

Fast ice, or landfast ice, floats on the water adjacent to the shoreline and can extend up to hundreds of kilometres, typically ending where water depth reaches over 20 m. Fast ice may range in thickness from less than one metre to many metres, with irregularities in both the surface and underside based on the movement of air and water around it. This ice is attached to the shoreline and does not move unless released into the current (at which point it becomes drift ice).

2.1.2 Drift Ice

"Drift ice" is essentially any floating sea ice that is not fast ice (WMO 2005). There are many different drift ice formations, but they can be divided into four major categories: pack ice; drift ice; grease, frazil and brash ice; and snow. Ice coverage in any area may change among these categories on a daily basis, or one kind of ice may dominate for a season (such as pack ice persisting through the winter).

Pack ice describes any concentrated ice cover that is not attached to land and exceeds *60-70% coverage* (WMO 2005, Dickins and Buist 1999). Pack ice may range from less than one metre to many metres thick. This ice typically moves with the water current.

Dynamic drift ice, which is sometimes referred to as "broken ice" may exist in the transition phases of freeze-up or break-up, persist throughout the winter in areas that do not reach full pack ice coverage, or exist at the edge of pack ice in the marginal ice zone (MIZ) (Økland 2000). Dynamic drift ice includes brash or slush ice as well as larger ice floes that move with the water current and wind. Irregular floes, often with "grease" ice or slush on the water's surface in between them, are impacted by wind and wave action, which may be greater closer to open water (Dickins 2005). Dynamic drift ice can be considered to be a collection of chunks of ice *up to 60-70% coverage* (above this would be pack ice,). Dynamic drift ice includes pancakes, ice cakes, and floes, all terms referring to different sized pieces of floating ice. In the spring melt, the chunks of ice may become "rotten" and honeycombed as the ice disintegrates.

Grease, frazil, and brash ice are smaller pieces of ice floating on the surface in thin (frazil), or thick (grease), slushy layers. Grease ice may solidify during freeze-up or diurnal temperature cycles to create pancake ice. Frazil or grease ice can appear anywhere there is open water, including between chunks of ice, or on leads or polynyas (see Section 2.1.4). These terms refer to ice during freeze-up; brash ice is the breaking-up ice chunks on the surface of the water during melt.

Drift ice can have areas of open water, which may be covered with grease ice during freeze-up and winter. It may feature large "ice keels" which protrude below its irregular surface and can gouge the sea floor as the ice moves (Dickins 2005). The underside of pack ice may be very rough and irregular. The outer edge of pack ice can be designated separately as the MIZ, often an area of intense biological activity at the edge of open water (AMAP 1998).

Snow begins as loose and granular precipitation. After collecting on land or ice-covered waters, it is highly variable based on diurnal and seasonal temperature changes, wind, precipitation or wave spray, and depth. Very deep snow can harden into ice (Owens *et al.* 2005). Snow landing on water may create a slushy layer.

2.1.3 Ice Development

Though some ice may persist through the summer melt (known as multi-year ice), the development of first year ice follows the simplified process outlined here. During freeze-up, the water surface may be covered with a thin slurry of ice, or a thicker slushy layer (Dickins 2005). As this ice solidifies into ice pancakes and then floes, a dynamic drift ice field is formed (Wilson and Mackay 1987). It may solidify fully into a pack ice formation, or remain as chunks of drifting ice. The process is not necessarily linear (some stages may not happen), and the amount of time each stage takes will vary considerably. The actual ice development process depends on a wide range of factors specific to any one location, including sea state.

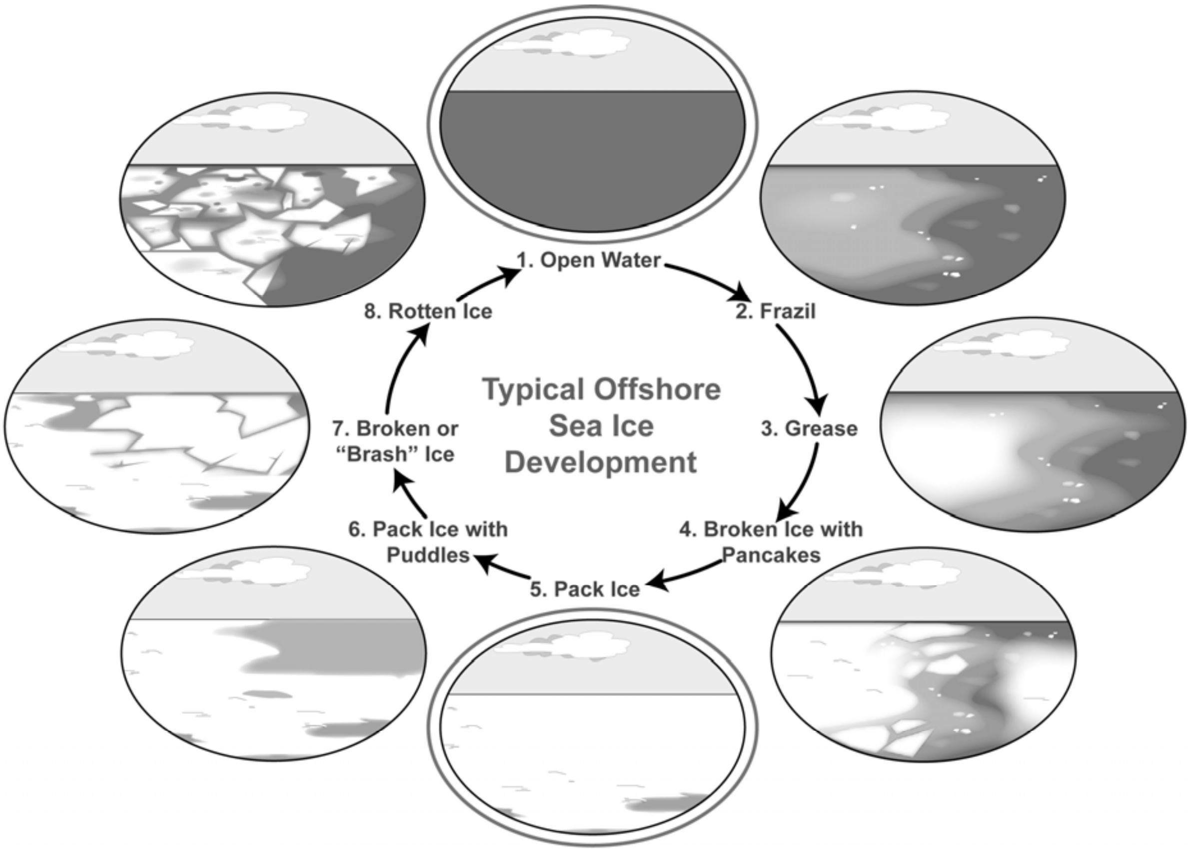


Figure 2-1. Typical offshore sea ice development

2.1.4 Structural Variations

In addition to being characterized by variability and transition, sea ice may feature several unique structures or formations that exist within and among the types of ice described above. For example, leads and polynyas are openings that can occur where fast and pack ice meet.

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. Leads may also be created using ice-breaking or ice management vessels (see Section 3.2.3.3).

2.1.5 Sakhalin Ice Regime

Sea ice is present seasonally in the Sea of Okhotsk, including around Sakhalin Island. Air temperatures stay below freezing for around 200 days each year, and sea temperatures just below freezing in the coastal zone (SEIC 2005c).

The ice regime off Sakhalin is highly dynamic. The approximate cycle of freeze-up and melt has been described in the SEIC's *Background Paper on Oil Spill Behaviour and Oil Spill Response in Ice Conditions: A Review*, as summarized in Table 2-1. Freeze-up generally begins in November or early December, with new drift ice forming amid grease and frazil ice, and moving at speeds ranging from 0.5 m/s to 0.8 m/s.

Table 2-1. Sakhalin Island ice conditions and cycle (Source: Dickins 2005 and SEIC 2005c)

Late November-December	Freeze-up begins. New ice drifts offshore and to the south at around 0.5 m/s and up to 0.8 m/s.
January-March	Dynamic drift ice dominates with coverage ranging from 20-80% (though pack ice—over 60% coverage—typically lasts for less than a month). The median floe size is around 100 m in diameter, with some as small as 20 m. When present, leads and polynyas can impact sea state by reducing the dampening effect of the ice. Ice is less than 1 m thick most of the time (90%). Ice keels of 10-15 km are often present, and can gouge the ocean floor in shallower waters. A strip of landfast ice is usually present.
April-May	Pack ice is broken up to small chunks.
Late May/early June-Oct/Nov	Ice is gone from the region.

During the winter ice season, from January through March, dynamic drift ice dominates with coverage ranging from 20-80% (though pack ice—over 60% coverage—typically lasts for less than a month). The median floe size is around 100 m in diameter, with some as small as 20 m. Ice is less than 1 m thick most of the time (90%). Ice keels of 10-15 km are often present, and can gouge the ocean floor in shallower waters. A strip of landfast ice is usually present during this time, although it may form, break up, and reform several dimes during the winter.

Spring break up begins in April or May, as the pack ice and drift ice break into smaller pieces and begin to melt away. The marine waters in the vicinity of the Sakhalin II development are generally ice-free from late May or early June through late October or early November.

The Sakhalin ice regime is dominated by dynamic drift ice in constantly changing formation. Section 3 considers how available oil spill response technologies perform under such dynamic ice conditions.

2.2 Behaviour of Oil in Ice Conditions

When oil is spilled on water, several weathering processes may take place. In ice conditions, weathering processes are different than those exhibited in warmer waters. For example, spilled oil may not spread as far in the presence of ice floes or irregularities in the ice surface because the ice may create natural barricades to oil movement (Evers *et al*. 2004). However, oil can move hundreds of kilometres from the spill site if it is trapped under or within a piece of ice. Trapped oil may not be released until complete melting takes place (Wilson and Mackay 1987, NRC 2003a).

Factors influencing the behaviour of oil in ice conditions fall into several categories, described in Table 2-2. The nature of the ice tends to dominate other factors in impacting the behaviour of oil after a spill (Evers *et al*. 2004). Ice coverage below 30% is not believed to significantly impact oil behaviour (Dickins and Buist 1999), although it has been observed to impact oil spill recovery activities (IT Alaska 2000, Robertson and DeCola 2001). Typically, 30% ice coverage or greater will significantly impact the behaviour of spilled oil (NRC 2003a).

In turn, the oil itself can impact ice formation by acting as an insulator (to slow ice formation) or speeding ice formation by reducing wave activity. In general, the presence of oil is considered to slow early ice development (Ross in Wilson and Mackay 1987). If gas is involved, as in a well blowout, the impact of the gas is most likely to cause ice fractures or heaving (Dome's Petroleum Ltd. in Fingas and Hollebone 2003).

Snow may become relevant to spill response if oil is released to, or moves to, the surface of pack or fast ice, or if it is released on land via a pipeline.

Table 2-2: Factors influencing the movement of oil in ice conditions

Category	Relevant factors
Nature of the ice	Type of ice (landfast, pack, or broken; first year, multi-year), presence of structural anomalies (polynas, brine channels, keels), texture on top and bottom, rate of freezing or thawing, movement
Properties of the spilled oil	Viscosity, boiling point, emulsification, volatility (ignitability), asphaltene and wax content
Location of the spilled oil	On top of ice (oil well blowout, tank spill, above pipeline spill, valve leak, vessel spill), or below ice (subsea drilling blowout, subsea pipeline leak, underwater valve malfunction)
Distribution of the spilled oil	Thickness of oil, whether it is pooled or sprayed, whether it has landed on ice and become integrated in the ice due to freeze-thaw cycle and/or snow fall
Weather and water	Wind, sea state, temperature, precipitation

2.2.1 Impact of Cold and Ice on Typical Oil Weathering

Weathering of oil spilled on open water is impacted by multiple factors, including the type of oil, temperature of the oil and the water, wind, current, tides, and weather (Table 2-3). The presence of sea ice and cold ambient temperatures will slow the weathering process. If the oil is frozen or trapped in the ice, the weathering process may halt completely until the oil is thawed and exposed to air and water, allowing the weathering process to resume. Oil viscosity will still increase in the presence of marine ice, but not as fast as in temperate open water because water uptake and evaporation will be slowed (Evers *et al.* 2004).

Evaporation, natural dispersion, and emulsification all impact the volume and surface area of the oil slick; each of these processes may be impacted by cold temperatures and sea ice. Evaporation rate is determined in part by the type of oil: generally, those components with boiling points below 200° C evaporate within 24 hours of a spill. Evaporation rates will be slowed by cold weather (Singsaas 2005). Just over 27% of the components in Sakhalin crude oil fall into this category.

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).

2.2.2 Impact of Ice Structure on Oil Behaviour

The presence of ice can impact oil behaviour by trapping the oil, controlling the rate of spread, and making it difficult to track. Observations from actual spills, laboratory experiments, and field studies provide some insight into the ways oil can interact with different ice formations. The oil and ice interaction is heavily influenced by whether the oil is released above or below the ice. Oil spills trapped under marine ice are examined in this report due to the risk of an under ice oil spill resulting from a subsea blowout or pipeline release from the Sakhalin II Project.

Oil released to open water amid dynamic drift ice will spread at the rate it would normally spread in the open water, areas, but spreading will be impeded by grease or frazil ice between the floes and the ice itself (NAR 2003). Due to the density difference between oil and water, spilled oil will likely rise to the surface of a slushy oil and ice mix (Martin *et al.* in Fingas and Hollebone 2003). The slick can also move underneath ice floes/pancakes, or be tossed on top of them in wave action causing bumping and moving of the floes (Wilson and Mackay 1987). There is no clear answer as to whether oil will move at the same rate as drift ice, or faster or slower (Evers *et al.* 2004), although some studies suggest that oil will move at the same rate and in the same direction as ice (Dickins and Buist 1999).

Table 2-3: Weathering processes impacted by sea ice (adapted from Evers *et al.* 2004)

Process	Open Water	Ice or Extreme Cold
Spreading and Dispersion	A thick layer of oil grows thinner and covers a larger area of water (depending on the oil).	Ice acts as physical barrier (drift 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% ice coverage, and with the ice at 60-70% (or greater) coverage. Unpredictable in dynamic drift 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 reduced due to dampening of wave activity by presence of ice.

The actual behaviour of oil spilled to grease or brash ice 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). Thus, it is extremely difficult to predict the movement of oil in this dynamic context.

Oil released under fast or pack ice will not spread as evenly as it might on the water surface. 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 therefore able to hold more oil pooling under its uneven surface. It is estimated that 1.5 million liters/km^2 of oil could be stored under late winter fast ice along the Alaska North Slope (Dickins and Buist 1999).

Oil trapped under ice may freeze and remain there as it cannot evaporate. The oil will move with the ice until the spring melt and may ultimately be released some distance from the spill site. This process has been referred to as "encapsulation" or an "oil-ice sandwich" (Evers *et al.* 2004, Izumiyama *et al.* 2004, NRC 2003a). A review of field tests and laboratory experiments finds that oil can be partially encapsulated within four hours and fully encapsulated as fast as 24 hours after contact with the ice (Fingas and Hollebone 2003).

Oil trapped under multi-year 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 oil could be trapped under multi-year 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).

Polynyas and leads can change oil behaviour as well. Areas of open water such as polynyas or 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 these 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 the ice. Water moving in or out of a lead can cause a "pumping" action, which moves oil out from under ice and into the lead. Pumping of oil into leads can be a dominant oil transport mechanism in the early hours of the spill (Reed *et al.* 1999).

Table 2-4 Behaviour of oil spilled to different types of ice environments (NRC 2003a)

If oil is spilled…	Sub-location	Fate during freeze-up	Fate after thaw
On water	<30% ice cover	As on open water	Melt to open water
	>30% ice cover	Mostly trapped in between ice	Melt to open water
	In leads	Frozen into ice	Melt to open water
	Frazil/ grease/ brash ice	Frozen into ice	Melt to open water
Under ice	1st year ice	Encapsulated	Rise via brine channels
	Multi-year ice	Encapsulated	Rise or remain in ice
Into ice		Encapsulated	Melt to open water
Onto ice	On ice	Pool & remain on surface	Melt to open water
	Under snow	Absorb into snow	Melt to open water

Ultimately, any oil that moves during initial spreading or while frozen in ice could end up on the shoreline. Here the hydrocarbons can mix with the sediment, form emulsions, or cover beaches, depending on the quantity of oil and state of weathering. Oil released under—or moving to—fast ice could reach the shoreline but be invisible to observers until break-up (AMAP 1998).

Oil spilled on snow, or which migrates through an ice sheet to a snow-covered surface, has not been fully studied and is difficult to track visually because it is obscured. One assumption is that oil in snow will eventually evaporate to the same extent as oil on open water, but it will require more time to do so. Limited testing has been conducted, and current models to estimate the evaporative rate in snow are inadequate (Buist 2000 in Owens *et al.* 2005).

Bacteria and some fungi will slowly degrade petroleum hydrocarbons spilled in the marine environment (AMAP 1998); however, degradation is slower in cold water areas than in temperate regions because the oil tends to be more viscous and not evaporate as quickly, making it less accessible to bacteria. (Atlas 1985, in AMAP 1998). Studies conducted on Alaska beaches that were oiled during the *Exxon Valdez* oil spill show that twelve years after the spill, oil was still present in the beach substrata and in a toxic, unweathered liquid form that remained biologically available (Short *et al.* 2004).

The behaviour of oil in different types of ice is summarized in Table 2-4.

2.2.3 Impact of Ice Season on Oil Behaviour

Oil behaviour in ice is heavily influenced by the season in which it is spilled. Oil spilled on fast or pack ice during fall freeze-up will likely migrate downwards as the ice develops and remain encapsulated, moving with the ice pack until the spring melt.

If oil is spilled in dynamic drift ice during fall freeze-up, it will become part of the ice floes as grease ice solidifies into pancake ice, and continues to build into solid ice formations. A rapid freeze can cause this to happen quickly, making oil recovery operations futile (Metge in Wilson and Mackay 1987).

When the spring melt starts, oil tends to move upwards through the ice and ends up pooling on top of it where weathering processes will take place and the remaining oil will eventually be released to the water wherever the sheet of ice ends up (AMAP 1998).

As first year ice begins to melt, brine channels open up in the areas where sea salt was concentrated by its exclusion from the ice formation. These opening channels can allow oil trapped in the ice, or under it, to rise to the surface (NAR 2003). This oil purging process will accelerate as spring temperatures rise above freezing. Thus, oil will increasingly appear on the surface of the ice and develop into thick pools of weathered oil. 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).

Figure 2-2 illustrates the interaction between spilled oil and a variety of ice configurations.

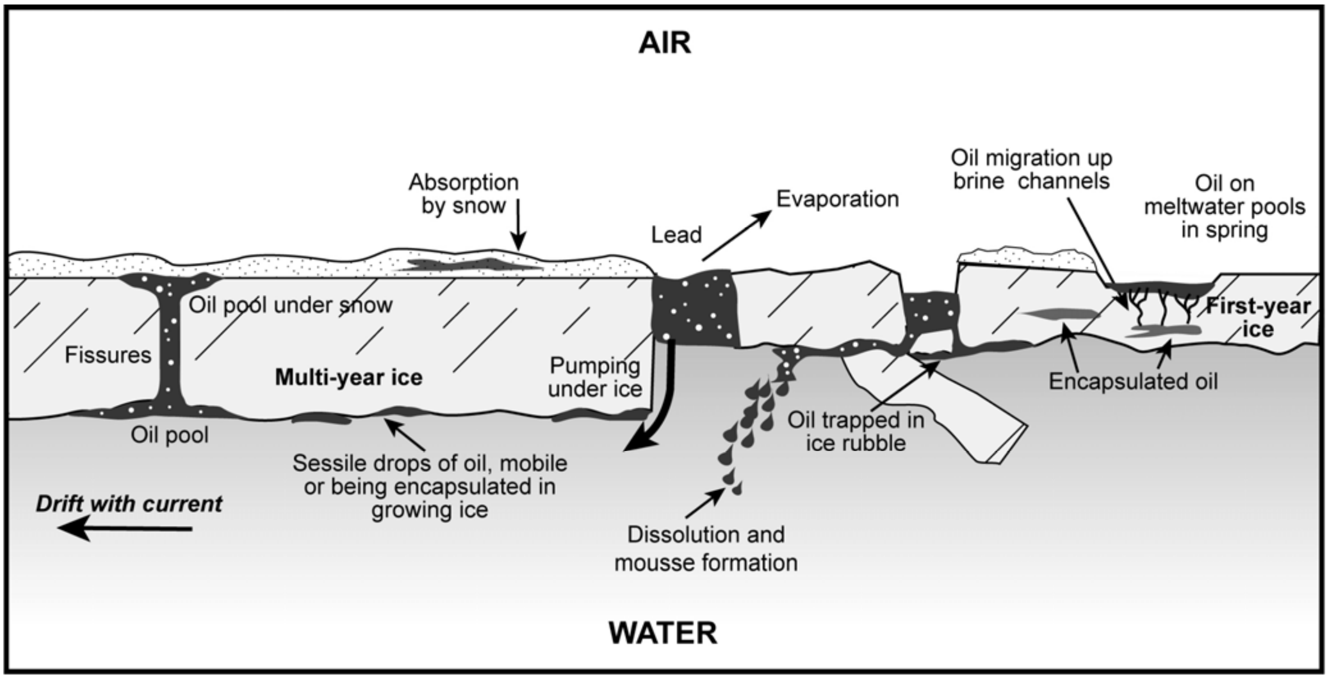


Figure 2-2: Oil-ice interactions (Bobra and Fingas in AMAP 1998)

2.2.4 Impact of Spill Source on Oil Behaviour in Ice

One of the most important factors influencing the behaviour of oil spilled on ice is the source of the oil spill.

Oil spilled from a tank or a guillotine leak of a pipeline will tend to develop thick oil pools near the source, later subject to distribution away from the source by wind, wave, and ice movement.

Oil distributed by a blowout is released high into the air or up through the water column due to the velocity produced by the subsurface pressure. Initially, oil mixed with drilling muds will be discharged from the well creating a pool of mud and oil around the well. The oil-laden drilling mud tends to land close to the well due to its density. Once the drilling mud is discharged from the wellbore, the well continues to release hydrocarbons, which can travel great distances away from the well, especially if the blowout is supercharged with natural gas released from the subsurface oil and gas reservoir at high pressures (Archer and Wall 1986). Oil released from a well blowout is propelled by natural gas and distributed by wind action, forming smaller and smaller droplets as it is deposited farther from the point of release (Dome's Petroleum Ltd. in Fingas and Hollebone 2003).

2.3 Predicting the Fate of Oil in Sea Ice

Predicting the fate of oil spilled in ice-infested waters requires new and improved algorithms to take into account the seasonal variation, weathering, and other factors, described above, that affect the behaviour 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 modelling the fate of oil in dynamic sea ice conditions. This section describes some of the models available, as well as their limitations.

2.3.1 Existing Theoretical Models

Numerous mathematical calculations have been developed to predict the behaviour of oil in ice conditions. Modelling of oil behaviour in ice began in the 1970s and continues to serve as the basis for much of the current theoretical models. Models tend to describe the behaviour of spilled oil in two categories: (1) on ice and (2) under ice.

In 1971, Fay and Hoult developed a semi-empirical model using three phases to explain the spread of oil on ice (gravity-inertia, gravity-viscosity, and interfacial tension-viscosity). Subsequent empirical models have been based on this work. Later efforts throughout the 1970s and 1980s explored the spread of oil theoretically, in the laboratory and using small field experiments. The sophistication of these models improved as additional physical parameters were added to the modelling algorithms such as the volume of spilled oil, time since spill, ice roughness, oil density and oil viscosity. Modelling experts continue to dispute the relative importance of various model inputs (Fingas and Hollebone 2003). Snow is excluded as a factor in most models.

The spreading of oil under ice has been studied in laboratory and field experiments. One model examined the space created by under-ice roughness by creating a mould of the underside of ice sheets (Goodman *et al.* 1987 in Fingas and Hollebone 2003). While the flow of oil under ice will be influenced by buoyancy, viscosity, and surface tension, most models predict that the spread of oil under ice is dominated by the subsurface shape of the ice unless strong water currents are present moving oil out of areas in which it might otherwise collect. In the case of a subsurface oil well blowout, a strong current can move oil and gas horizontally in the water column before reaching the ice (Fingas and Hollebone 2003).

Fewer efforts have been made to quantify the movement of oil in dynamic drift ice or amid smaller chunks of ice such as grease or brash ice; these conditions introduce more variables and are inherently more challenging to predict. One model was developed to modify the original equation developed by Fay and Hoult, but it needs additional testing for validation (Fingas and Hollebone 2003). Sayed *et al.* (1995) concluded that oils with low viscosity will spread farther in brash ice than more viscous oils. Yapa and Weerasuriya (1997) developed a theoretical model to be used for oil behaviour under drift ice by modifying earlier work on oil under ice to account for seepage into cracks, but this represents only a first step; significant work remains in this area.

2.3.2. Challenges to Modelling

Upon reviewing theoretical models of oil behaviour 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. Some of the early models are now antiquated due to the development of improved measuring methods. Reed *et al.* (1999) concluded the ice leads play a dominant role in impacting oil behaviour but are not incorporated in most models. It is especially challenging to develop accurate modelling algorithms to predict the behaviour of oil over time, because the characteristics of the oil are constantly changing.

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 order to improve oil spill modelling 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 behaviour in sea ice conditions, models developed for one region of the arctic may require some adjustment before being applied to other cold-weather regions. Currently, data is available for only a limited range of oil and ice types (Singsaas and Reed 2006). Very little data is available regarding the fate and behaviour of Russian crude oils and crude oil products in ice-infested waters (Singsaas 2005).

2.4 Impacts to Wildlife

Oil and gas exploration, extraction, and transport can impact wildlife several ways, from the acute and highly visible effects of a large spill to the less obvious, longer-term impacts of ingestion or uptake of toxic substances. In any marine environment, wildlife impacts from oil spills can be considered in three categories:

- **Physical contact** with the oil in any part of the water column or on shore can reduce the insulating capacity of fur or feathers, leading to hypothermia, or hindering the flight or buoyancy of birds (EPA 1999).

- **Toxic contamination** by ingestion, inhalation, or absorption (in the case of eggs) could damage the digestive system, liver, or lungs. Contaminants can be ingested one time after a single spill event, over years in areas of oil activity or situations with low level releases, or through the food chain as they are passed to higher trophic levels in the process of bioaccumulation (Hobson 2002). Inhalation of fumes can also lead to fatal brain lesions, stress, and disorientation (Loughlin in Peterson *et al.* 2003).

- **Resource scarcity** caused by inaccessible food can impact both resident and migratory populations (EPA 1999).

Ice conditions may impact the magnitude or severity of wildlife impacts in several ways.

- Due to slower rates of biodegradation and dispersion, as well as longer life spans and slower generation turnover (for benthic species), recovery will take longer in these areas (AMAP 1998).

- When considering wildlife impacts, the timing and location of a spill are more significant factors than the quantity of oil spilled (AMAP 1998). Leads, polynyas, and ice edges, tend to be focal points of biological activity (Stirling 1995), and also the most likely recipients of pooled oil spilled to the surface, impacting birds or bears fishing in these areas, and marine mammals using them to breathe.

- Since oil can be trapped in ice and released during the melt with minimal signs of weathering, a fall or winter spill can transfer wildlife impacts to the spring or summer. Thus arctic oil spills not only affect resident populations present at the time of the spill, they also affect migratory species seasons later.

Whales are at risk of encountering newly spilled oil—or oil released from ice—when breathing at the surface and feeding on benthic organisms. Some cetaceans appear to be able to avoid oil, but whales have also been observed moving through it (NRC 2003b).

There is no data regarding the impact of oil spills on western gray whales, but migrating eastern gray whales have been associated spatially and temporally with two major US oil spills. Three dead gray whales were found during the northward migration after the 1969 *Union Oil* spill in Santa Barbara, California (Brownell 1971 in ISRP 2005), while 26 dead eastern gray whales were found after the 1989 *Exxon Valdez* oil spill in Alaska (Loughlin 1994 in ISRP 2005). Although oil was present on these carcasses, the animals had been dead for weeks to months and the carcasses were too decomposed to determine the cause of death.

The number of eastern gray whale strandings after the *Exxon Valdez* oil spill was considerably higher than previous years (Zimmerman 1989 in ISRP 2005), although the interpretation of this information is complicated by the fact that search efforts for carcasses greatly increase after the spills.

Although the direct effects of oil ingestion cannot be determined from known exposures of gray whales, they can be inferred from exposures in other species. Ingested petroleum hydrocarbons have been shown to be toxic to all mammals investigated to date. Ingestion of oil is likely to cause some adverse effects on gray whales, depending upon the dose and type of oil ingested (ISRP 2005). Research on oil spill impacts to bowhead whales show that spilled oil may have significant negative impact to those whales' organ systems (NRC 2003b).

While scientists believe benthic communities in the arctic and sub-arctic will be damaged by an oil spill, there are no documented, long-term field studies to address this. The toxicity of the oil and its ultimate fate may be determining factors.

After the *Exxon Valdez* oil spill in Alaska in 1989, ecosystem impacts have been documented more thoroughly and over a longer time period than previous spills and experiments. The 1989 spill caused significant acute-phase mortality as well as long-term impacts. Oil persisted at least through a 2001 study, which found over 55,000 kg of oil from the spill still present in sediments, and corresponding impacts, including enhanced mortality of seabird and sea otter populations that interact with the sediments. Some populations' exposure to sublethal levels of petroleum also impacted the health of subsequent generations, as manifested in size, weight, and life span (Peterson 2003), because larvae and eggs of fish may suffer damage disproportional to that of adults (AMAP 1998). A series of cascading effects has also been described in the years following the spill, caused by impacts to one population which change its interactions with others (Peterson 2003).

2.4.1 Potential Effects of a Sakhalin II Oil Spill

In spite of decades of study and observation, it remains difficult to predict the exact impact a spill in any one location may have on local or migratory wildlife. The factors are numerous: time, location, season, species present, source of the oil spill, type of oil and conditions dictating weathering, and the timing and quality of a response. Predicting the behaviour of oil in ice conditions is a challenge; predicting the behaviour of, and impacts on, associated species over an unpredictable area and time of impact is an immense task.

The potential impacts of a spill from the Sakhalin oil and gas development to local wildlife, particularly the critically endangered WGW, are likewise difficult to foresee. Any oil spill scenario that results in increased levels of hydrocarbons in benthic and epibenthic invertebrates (from sunken oil or burn residue resulting from response operations; see Section 3) or plankton could contaminate and potentially harm the WGW off Sakhalin. The benthic species most prevalent in whale scat occurs almost exclusively nearshore (Gerzig *et al.* in ISRP 2005), indicating the focused nature of the whales' feeding. Release of oil during the melt could coincide with the arrival of the whales on their northward migration; this group would include calves, which are usually born on the northward trip (ISRP 2003) and could be more vulnerable to oil impacts than an adult whale. Nearshore areas are vulnerable to re-oiling for long periods of time after a spill from stranded oil on the shoreline.

A recent analysis of oil spill risks to WGW feeding areas near Sakhalin finds that, because the whales feed on such a large volume of food, contamination of their feeding grounds could result in considerable oil ingestion and cause the whales significant harm. "[I]f oil comprised 10% of 1600 kg of food consumed by a 40-ton whale, the total ingested oil would be 160 kg per day, which, depending on the duration of the exposure, could be lethal" (ISRP 2005).

3. Review of Existing Oil Spill Response Technologies and their Application in Dynamic Ice Conditions

Oil spilled to water bodies where sea ice is present may become trapped on top of, below, or within ice. Sea ice will impact the weathering and transport of spilled oil, and has the potential to complicate spill tracking, containment, and recovery operations. Ice can also impact logistical aspects of spill response operations, such as safe operation of response vessels or positioning of equipment.

Most technologies used in responding to oil spills in sea ice have been adapted from those typically used on open water and land. While some on-water response technologies may be transferable to open water arctic conditions, sea ice has been demonstrated to reduce the efficiency of many response methods (AMAP 1998).

The formation, thickness, and percentage of ice coverage all affect the selection of response technologies, as do the characteristics of the spilled oil, which, as discussed, can be impacted by sea ice.

Fast ice is often considered a favourable condition for mounting spill response operations, because equipment and personnel can be deployed from the ice. However, this requires sufficient ice thickness to support equipment and personnel. Ice thickness may be artificially enhanced by spraying the ice with successive layers of water and allowing them to freeze. However, the development of "ice roads," as they are commonly called, can take days or longer.

Pack ice can sometimes be thick enough to support ground transport or helicopters as well. However, even if pack ice is sufficiently thick to support heavy equipment, it may still move unpredictably, making response operations unsafe. Figure 3-1 shows the minimum required ice thickness to support a range of heavy equipment. Maximum estimated thickness of landfast ice at Sakhalin is 1.6 to 1.7 m, which could support some types of heavy equipment in areas where contiguous ice exists. However, the ice conditions are highly unstable and the landfast ice may appear and disappear several times in one ice season (Dickins 2005).

Dynamic drift ice cannot support equipment or personnel, so response operations must generally be mounted from vessel or aerial platforms. Depending on the percentage of ice coverage and the condition of the ice, vessels may be able to deploy response equipment or countermeasures between ice floes. However, dynamic drift ice can damage machinery and interfere with many response technologies.

Like drift ice, spill response in grease, brash and frazil ice is also usually vessel-based. The grease and frazil ice that occur during freeze-up pose a particular challenge to response vessels and recovery equipment. Slush ice is particularly challenging for mechanical recovery.

Snow may benefit or hinder a response, depending on where the snow builds up. Deep snow on solid ice may absorb oil which can then be recovered by melting the mix; however, snow cover may also hide oil spilled to solid ice. Snow that lands on thin or dynamic drift ice can further complicate response by obscuring ice conditions.

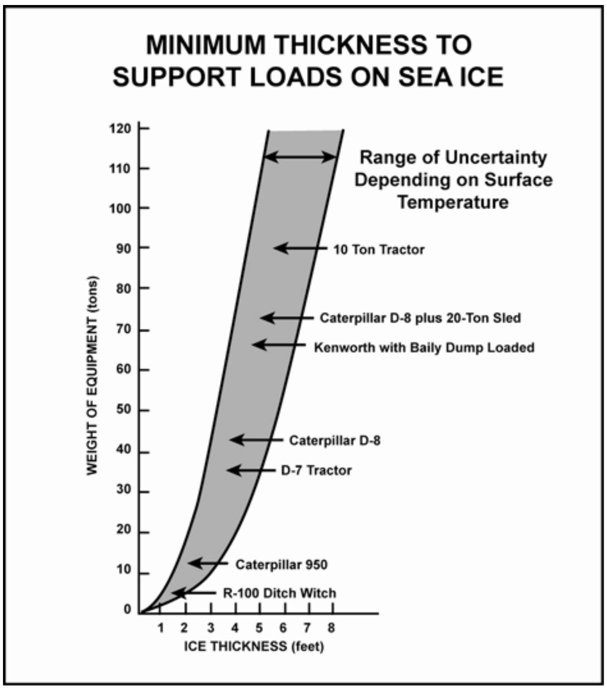


Figure 3-1: Ice load requirements (Nuka Research 2005, ACS 2003)

This section considers the applicability of on-water spill response technologies in the presence of sea ice, and also reviews technologies and techniques that have been developed specifically for oil spills in dynamic marine ice conditions. Because the predominant ice conditions at Sakhalin involve dynamic drift ice (Dickins 2005), this section focuses on the applicability of spill response technologies in broken sea ice conditions. This section considers the potential applicability and limits of surveillance and tracking, mechanical recovery, in-situ burning, chemical dispersants, and blowout control as response options for oil spills in dynamic ice conditions.

3.1 Surveillance, Tracking, and Detection

In order to mount an oil spill response, information about the location, movement, and characteristics of the oil spill must be considered. Selection and application of response technologies depends on the location and movement of the oil, surface layer thickness, and the nature and extent of weathering. This information is especially important in marine spills where sea ice is present.

Real-time oil and ice surveillance and tracking are critical to response operations. Information about the location, thickness, and movement of the oil slick and the ice is essential to incident planning, selection of response techniques, and coordination of safe vessel operations. Real-time information about ice coverage and oil location must be continuously communicated to spill managers and response personnel to facilitate on-water response operations.

3.1.1 Available Technologies

Numerous technologies are available to detect and track oil spills on open water and ice. Techniques and equipment that are commonly used on the Alaska North Slope and other arctic regions are described here (Glover and Dickins 1999, Dickins and Buist 1999, Owens *et al.* 1998).

Tracking buoys may be used to follow the movement of the oil slick in response to winds, surface currents, and ice movements. Buoys released into an oil slick move with the oil and ice, providing continual data on the location and movement of oil for up to several months after the initial release. Tracking buoys emit a signal that may be monitored using either satellite technology or radio transmissions. Satellite tracking buoys use Global Positioning System (GPS) technology and deliver real-time position information. Radio tracking buoys emit signals in bursts from a radio transmitter built into the buoy. These signals are tracked by the receiving equipment, which can be placed onboard vessels of opportunity, or fixed on aircraft. Figure 3-2 shows examples of tracking buoys.

Satellite imagery may be available to provide real-time images of ice conditions and possibly oil slicks. Satellite images generally lack the resolution necessary to detect small oil slicks directly, but in combination with tracking buoys, satellite imagery can provide a clear picture of the ice conditions in the vicinity of the oil.

Airborne reconnaissance may be conducted using a range of technologies, including visual observations, still and video cameras, or **remote sensing** using infrared (IR) and ultraviolet sensors (UV), laser fluorosensors, and radar.

Trained visual observers can be deployed in combination with remote sensing equipment to identify oil slicks; however, it is difficult to differentiate between oil slicks and other observations such as silt on ice, cloud shadows on water, and wind patches, which may appear similar to oil.

Airborne and space remote sensing technologies utilize two categories of sensors: active, which provide their own sources of excitation or illumination, and passive, which rely on a secondary source (such as infrared). The laser fluorosensor is considered the most useful of the active sensors, but it is expensive and large (Fingas and Brown 1997). Remote sensing using acoustic methods has shown some promise when compared to other methods (Fingas and Brown 2000).

Ultraviolet systems may be used in conjunction with IR to differentiate between thick and thin sections of the slick. Although uncommon, oil can become submerged beneath the water surface (because the oil is more dense than water), making it extremely difficult to track using visual methods. Figure 3-3 shows airborne reconnaissance with aircraft-mounted forward-looking infrared (FLIR) sensors.

Vessel surveillance may also be used to track oil and ice position and movement. Visual observations, still and video cameras, or sensing equipment may be deployed from a response vessel or vessel-of-opportunity. The accuracy of visual observations from vessels may be limited by visibility factors. Figure 3-2 shows vessel surveillance.

Optical methods (still and video cameras) can record overall spill location and slick boundaries in reasonable light conditions. However, they do not provide a good indication of slick thickness and can cause confusion in low light conditions. Infrared systems are effective in documenting offshore slicks while temperature differences exist between the oil and water.

On-ice surveys may be used when the ice sheet is thick enough to support personnel and equipment. Handheld GPS units may be used to document locations and extent of spills in conjunction with spill survey activities. Under-ice lights, slots, trenches, bore holes, and other techniques may be used to identify and track ice location and movement. Remote sensing technologies have also been tested to track oil under ice.

Trajectory models may also be used to map or predict the movement of oil and ice. In open water, surface oil trajectories are developed based on the wind speed and direction and the current. Modelling submerged oil is often more difficult due to limited subsurface current data in many geographic areas (see discussion in Section 2.3). In drift ice, surface oil usually moves at the same direction and speed as the ice. Predicting the movement of oil under ice can be more complicated.

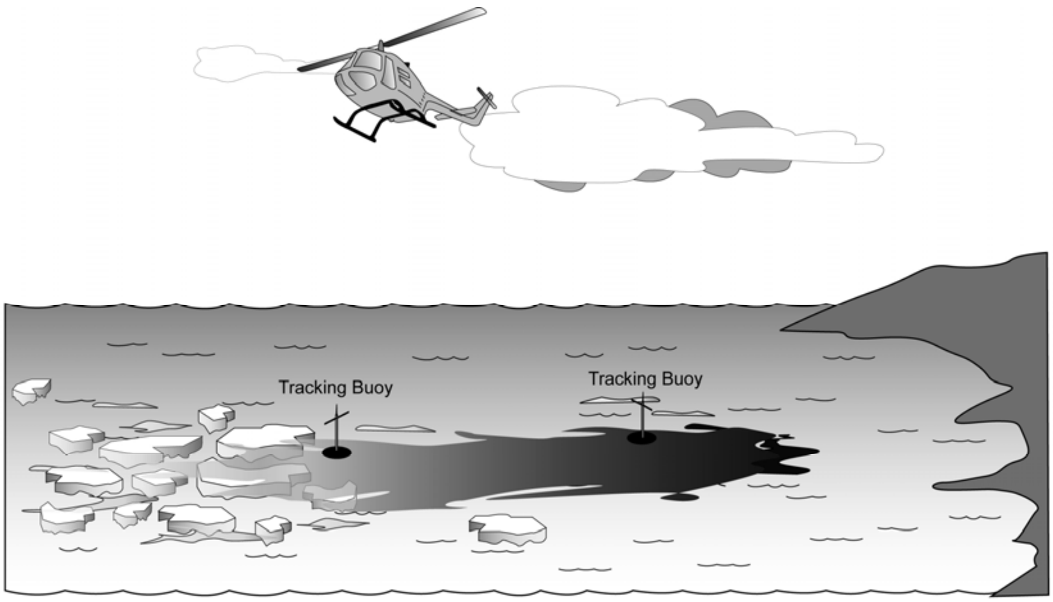


Figure 3-2: Tracking buoys in oil slick with ice (Nuka Research 2005, ACS 2003)

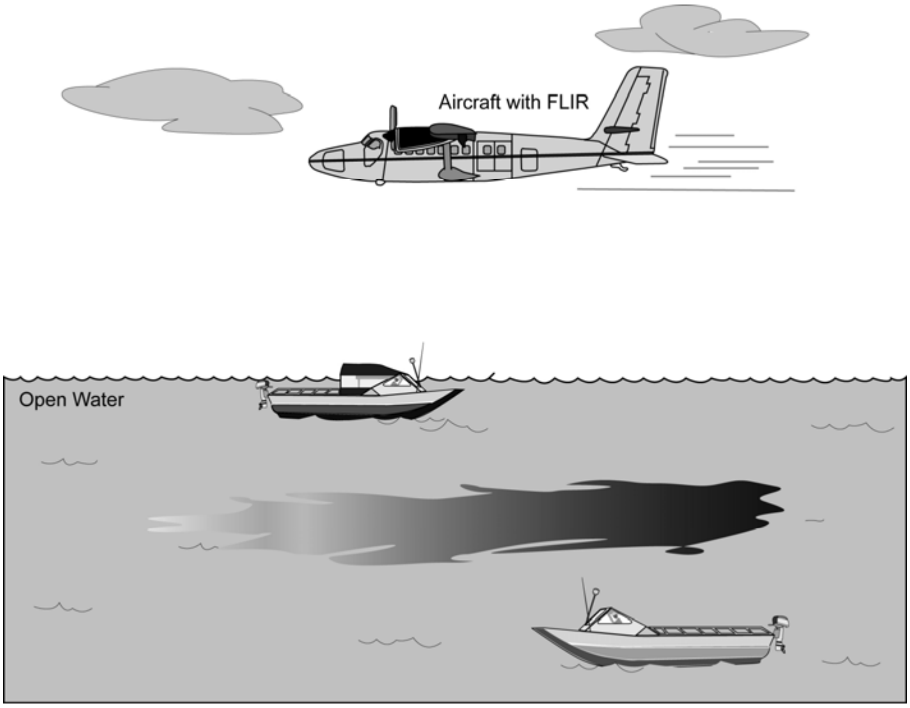


Figure 3-3: Airborne reconnaissance and vessel surveillance to track oil slick (Nuka Research 2005, ACS 2003)

3.1.2 Limits Imposed by Dynamic Ice Conditions

Estimates vary regarding the impacts of sea ice on spill surveillance and tracking. Response experts often use 50% ice coverage as a rule-of-thumb for defining the extent to which open water detection and mapping may be applied. When ice coverage exceeds 50%, methods such as visual observation become much less reliable because of problems in detecting the presence of oil in ice leads; however, remote sensing technologies may still apply. Moving ice and decreased daylight can further complicate tracking efforts (Glover and Dickins 1999).

Airborne systems such as laser fluorosensors and IR sensors have shown some potential for detecting and mapping oil among drift ice. The latest generation of high resolution radar satellites could be used to map large spills in an open pack condition, but radar signatures of new ice, oil, and calm water can be very confusing. Dickins and Buist (1999) recommend that "further work is needed in this area before satellite imagery can be recommended as an operational tool," and conclude that visual airborne reconnaissance remains the most effective method of oil and ice surveillance. However, these methods are subject to weather and daylight constraints. During the *M/V Selendang Ayu* oil spill in Unalaska, Alaska, satellite imagery provided a more detailed picture of oil spreading than overflight observations (AAI 2004).

Additional tests on remote sensing in ice were recently carried out in Norway, using a spill-of-opportunity. Initial reports from these trials indicate that a sled-mounted sensor using radar technology was successful in sensing oil under fast ice (Munson 2006).

3.2 Mechanical Recovery

Mechanical recovery of oil spills in open water or nearshore environments involves the physical containment of the oil within natural or man-made barriers and the subsequent removal of the oil from the surface. The objective of mechanical recovery is to concentrate oil to a thickness that will permit recovery. Mechanical recovery systems involve three major components: containment barriers, recovery systems, and secondary storage for recovered oil and water. Mechanical recovery systems are supported by additional equipment and resources such as vessels, pumps, anchors, decanting systems, and trained personnel with the ability to safely operate these systems.

3.2.1 Available Technologies for Open Water Mechanical Recovery

Containment barriers are used to intercept, control, contain, and concentrate spreading oil. The equipment most commonly deployed as an on-water containment barrier is oil boom, which comes in a variety of forms and may be deployed in a number of possible configurations. Sea ice may act as a natural containment barrier under certain conditions. Subsurface containment barriers, such as oil trawls, may collect and concentrate submerged oil, although experience with oil trawls is limited.

3.2.1.1 Booming

There are a variety of commercially available oil containment booms. The boom extends both above and below the water surface. The portion of the boom above the water surface is referred to as the sail and usually includes a flotation mechanism; the portion below the surface is referred to as the skirt. The boom may be held in place by anchors, vessels, or specialized boom positioning devices such as trolleys. A combination of methods may be used to position boom.

Containment booming is a fixed-booming tactic where boom is positioned around the spill source to prevent spreading and concentrate the oil for removal with a skimmer.

Diversion booming redirects oil to a specific location for recovery. Diversion booming is usually associated with water bodies where currents, winds, or other forces create a directional flow of oil.

Exclusion booming may be used to prevent oil from entering a sensitive area. Exclusion booming is not necessarily associated with oil recovery, although oil that is excluded may be collected and concentrated for recovery using containment or diversion booming.

Deflection booming is used to direct oil away from a location or to change the course of an oil slick. It is differentiated from diversion booming because in deflection booming, oil recovery is not attempted.

Figure 3-4 shows three typical containment boom configurations used to concentrate oil for removal with skimming systems or recovery devices. Figure 3-5 shows examples of diversion, exclusion, and deflection booming.

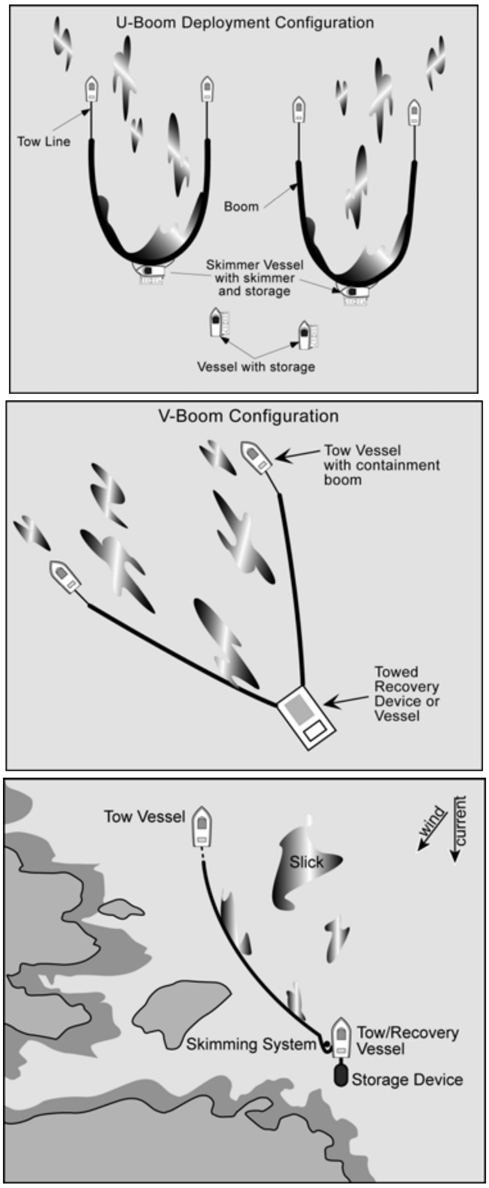


Figure 3-4: Three typical containment boom configurations (U-boom, V-boom, J-boom) (Nuka Research 2005, ACS 2003)

3.2.1.2 Skimming Systems

Recovery of oil contained or concentrated with boom 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 secondary containment, where the oil and water can eventually be separated for disposal. Like booms, there are many models of skimmers, but all fall into one of three categories.

Weir skimmers draw liquid from the surface by creating a sump in the water into which oil and water pour. The captured liquid is pumped from the sump to storage. Figure 3-6 shows a variety of weir skimmers.

Oleophilic skimmers pick up oil adhered to a collection surface, leaving most of the water behind. The oil is then scraped from the collection surface and pumped to a storage device. The collection surfaces in oleophilic skimming systems include rotating disks, brushes and drums, or continuous belts or ropes. Figure 3-7 shows examples of oleophilic skimmers.

Bucket skimmers are a variation of a weir or oleophilic brush skimmer that can be used in either mode. A bucket skimmer is mounted on an articulating arm that allows the skimmer head to be quickly moved from one pool of oil to another. Its dual mode allows it to process pools of oil on ice and in the water.

Suction skimmers use a vacuum to lift oil from the surface of the water. These skimmers require a vacuum pump or air conveyor system. Like weir skimmers, suction skimmers may also collect large amounts of water if not properly operated. Most suction skimmers are truck mounted and work best on land. However, suction skimmers for the marine environment have been made by converting fish pumps to oil recovery purposes, or loading a vacuum truck on a vessel.

3.2.1.3 Storage Devices

Storage devices are an important component of mechanical recovery, and can impede the recovery rate if insufficient capacity is available to store recovered liquids. Recovered liquids generated during mechanical recovery include emulsified oil/water and free water. Oil storage devices for the marine environment include: tanks, bladders, drogues, and barges. Portable oil storage devices may be stored onboard or can be towed by a vessel.

In order to effectively implement mechanical recovery, sufficient storage volume must be available to handle recovered liquids. Typically, during open water response operations, 10 to 20% of the recovered liquids will be free water. Oil/water emulsions can contain as much as 60% water, so as little as 30% of the recovered liquids may be oil. For example, if a mechanical recovery system was designed to recover 1,000 tonnes oil, as much as 3,000 to 3,500 tonnes of storage capacity might be required, depending on the percentage of oil in the oil/water emulsion. The water content of oil recovered from within sea ice may be significantly lower than 60%; regardless, storage capacity should be sufficient to handle additional volume from recovered water.

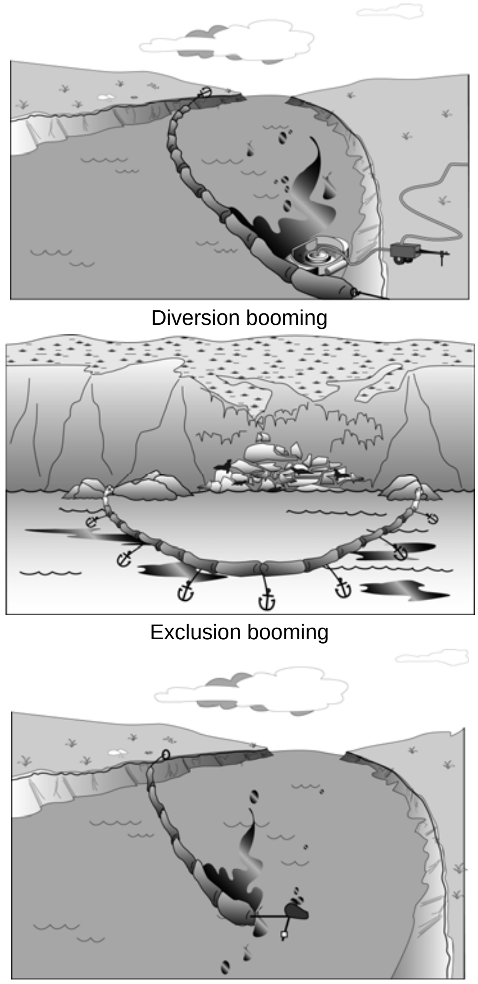


Figure 3-5: Diversion, exclusion, and deflection booming strategies (Nuka Research 2005, ACS 2003)

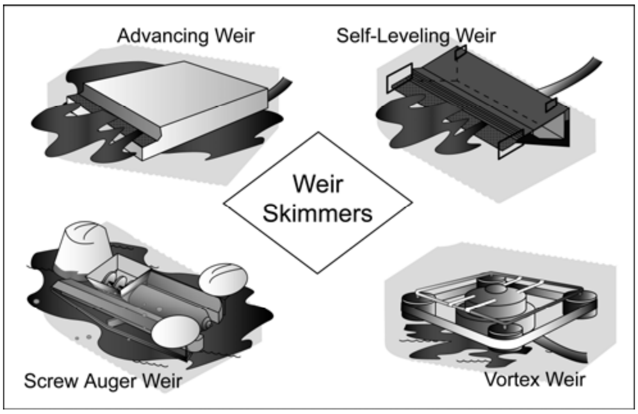


Figure 3-6: Weir skimmers (Nuka Research 2005, ACS 2003)

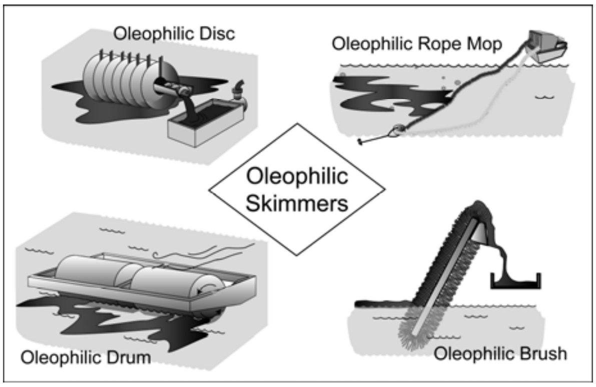


Figure 3-7: Oleophilic skimmers (Nuka Research 2005, ACS 2003)

3.2.1.3 Deployment in Dynamic Ice Conditions

The Northstar offshore oil and gas production facility in Alaska completed a best available technology (BAT) analysis of mechanical recovery equipment as part of their state-required oil spill contingency plan. This analysis considers the use of boom and skimmers during freeze-up and break up ice conditions in the Alaskan Beaufort Sea.

The Northstar BAT analysis identifies three types of large inflatable containment boom that have been demonstrated effective in ice-infested waters (RoBoom 1500/2000 series, Sea Sentry II 20-30, and Nordan 600 and 350 Ocean), one type of large rapid deployment boom (Nofi Ocean), and three types of small boom. Two fence booms (Slick Bar Mk7 and Globeboom) and foam log boom are described as potentially effective in early freeze-up and break-up conditions, although the foam log booms are not as robust as the fence booms. All booms (large and small) are considered to function better in break up than freeze-up. Boom effectiveness rapidly decreases as freeze-up conditions progress to higher ice concentrations (BPXA 2003).

The Northstar BAT analysis (BPXA 2003) considers several types of skimmers, and concludes the following regarding their effectiveness in ice-infested waters:

- LORI® brush pack, LORI® or Lamor drum brush, and Aqua-guard drum brush skimmers (oleophilic) are rated to operate in widely dispersed, newly forming ice but not in a continuous growing ice cover. Freeze-up conditions significantly limit encounter rates.

- Elastec TDS-118 and TDS-136 drum (oleophilic) skimmers are not considered capable of functioning in Beaufort Sea freeze-up conditions, because they rapidly clog with ice.

- Foxtail rope mop skimmers (oleophilic) and conventional rope mops can recover oil until ice becomes a continuous cover, but have problems at sub-freezing temperatures because the rope mop freezes.

- Desmi 250 skimmers (weir) have limited effectiveness in ice-infested waters. The skimmer clogs at the screw auger pump and has low encounter rates in ice.

- JBF dynamic incline plane (DIP) skimmers (suction) can operate in widely dispersed, newly forming ice but not in a continuously growing ice cover. They are not considered appropriate for use in ice-infested waters because the skimmer becomes blocked by ice pieces, and becomes inefficient at recovering oil in the presence of slush ice. Significant encounter rate limits apply during freeze-up.

- The Transrec 250 (weir) skimmer is ineffective in most ice-infested waters because of ice clogging the weir.

- Marco Belt Class Vessel-of-opportunity (VOSS) skimmers (suction) are considered to have limited capability in ice-infested waters. They would be most appropriate in newly forming, widely dispersed ice.

A few tactics have been developed to mechanically recover oil in sea ice using on-land and on-water response equipment, with some adaptations. In fast-moving water with sea ice present (as in spring break-up in rivers), recovery may be possible in areas where the ice provides natural containment. For oil trapped under ice, an auger may be used to bore a hole into the ice, or a trencher to cut a slot into the ice, and then recovering the oil with a pump. An alternative method involves boring or cutting two holes into the ice and then running a rope mop skimmer along the underside of the oiled ice to collect the oil. These methods, which are displayed in Figure 3-8, generally require ice that is thick enough to support personnel and equipment (Figure 3-1).

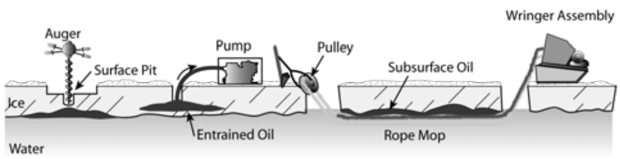


Figure 3-8: Oil recovery from under ice (ACS 2003)

3.2.2 Limits to Mechanical Recovery in Dynamic Ice Conditions

Response experts generally agree that conventional open water mechanical recovery technologies operate at significantly lowered efficiencies when sea ice is present (Abdelnour and Comfort 2001). Sea ice, particularly dynamic drift ice, affects the functionality of both boom and skimmers, the primary components of mechanical recovery. Sea ice also impacts vessel operations and may limit or preclude the ability to operate certain classes of vessels. Cold weather conditions can further complicate mechanical recovery, causing efficiency losses for both personnel and equipment (see Section 4).

The presence of dynamic drift ice interferes with the ability to contain oil with sufficient thickness to recover it. Oil tends to disperse and mix into the ice, making it necessary to separate the oil from the ice in order to clean up the spill. 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 to recover oil by lowering the encounter rate (rate at which skimmer comes into contact with pooled oil) and increasing manoeuvring and repositioning time to place the skimmer for optimum recovery among ice floes (Abdelnour and Comfort 2001, Fingas 2004).

Conventional marine operations in dynamic drift ice are vulnerable to rapid changes in weather and ice conditions, and significant down time often occurs due to the movement of ice in response to wind conditions and sea state (Dickens and Buist 1999). Figure 3-9 shows examples of ice interfering with mechanical recovery equipment during dynamic ice response trials on the Alaska North Slope in 2000.

The limits of open water mechanical recovery systems in sea ice conditions have been correlated to the percent coverage of sea ice. However, as ice concentrations increase, the potential for the sea ice itself to serve as oil containment increases. Dickins and Buist (1999) found that ice concentrations of 60% or higher provide "an effective means of reducing oil spill spreading." Yet, while the spreading rate is diminished the recovery rate can be severely impacted by the logistical inaccessibility of oil accumulations because of vessel, mechanical and human limitations. Limits to vessel operations at higher ice concentrations make recovery operations extremely difficult. Bucket skimmers that can be deployed from vessels with a mechanical arm have shown some promise for removing oil that is contained in ice pockets under these higher ice conditions.

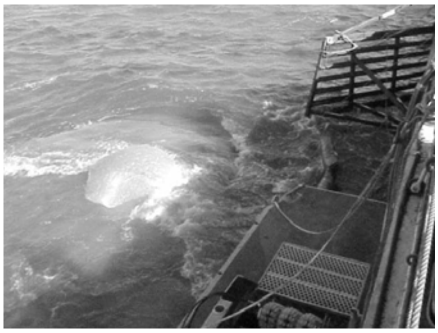
In ice concentrations below 60%, additional containment is usually required to concentrate the oil so it can be recovered by mechanical skimming devices. Dickins and Buist (1999) found that most containment booms can be used in light brash ice conditions and ice concentrations up to about 30%. Based on these estimates, ice conditions ranging from 30% to 60%

coverage may present the biggest challenge to mechanical response, as conventional booms are likely to be ineffective, but ice conditions are not sufficient to afford natural containment of spills (Evers *et al.* 2006, Glover and Dickens 1999).

Results from other tests and trials generally support the 30% rule, although dynamic drift ice conditions have been demonstrated to significantly reduce recovery efficiency in ice conditions down to 10% coverage. During a series of equipment trials in dynamic ice on the North Slope in 2000, a barge-based mechanical recovery system was demonstrated to be somewhat effective in ice conditions up to 30%, but only if ice management systems were deployed to reduce the amount of oil present at the skimmer to 10% or lower. Sea ice caused considerable strain on containment boom and boom failure was a problem (Robertson and DeCola 2001). The trials demonstrated that the maximum operating limit for the barge-based mechanical recovery system in ice-infested waters was 0-1% in fall ice, 10% in spring ice without ice management, and 30% in spring ice conditions with extensive ice management (NRC 2003b).

BP's oil spill contingency plan for an offshore oil and gas facility in the Beaufort Sea supports the 10% limit, noting that at concentrations above 10%, the containment boom concentrates ice as well as oil, and the ice concentration proves problematic for recovery systems (BPXA 2003).

Aside from the challenge of containing oil spilled in ice-infested waters, recovery operations may also be complicated by the presence of ice. Most skimmers operate at a significantly reduced efficiency, or not at all, when drifting ice pieces are present within the oil slick. Some skimmers may be effective recovering oil between the cracks in ice leads, but quickly shut down as ice forms. Positioning the skimmer in ice-free areas can be challenging in ice conditions as well. Mechanical recovery operations in ice-infested waters are generally more effective on a small scale, such as collecting oil from small leads within ice floes using portable over-the-side skimmers or mobile units.



Sea ice interferes with skimmer

Ice conditions interfere with boom.

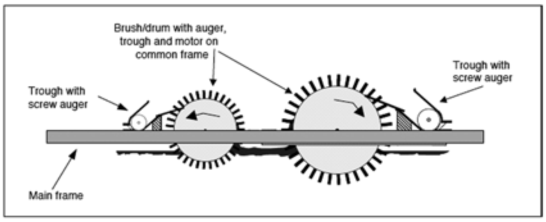
Ice conditions cause boom failure.

Figure 3-9: Effects of sea ice on mechanical recovery equipment. (Alaska Department of Environmental Conservation photographs, 2000)

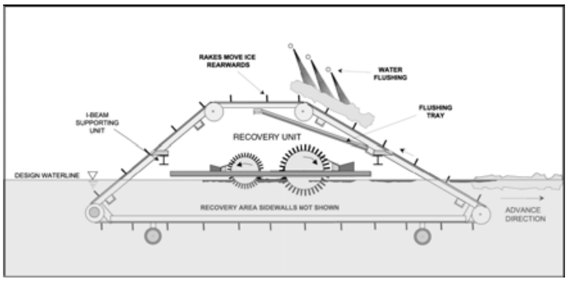
An SEIC report that considers the challenges of using mechanical recovery to clean up a large oil spill from Sakhalin II concludes that the scale of a response reliant on small batch mechanical recovery for a spill of 136 tonnes or more would be untenable. The report notes that "the number of systems required to recover even 10% of the spill becomes unmanageable. There is little to be gained in these cases from bringing in more than a few vessels.” (Dickins 2005)

The need to improve mechanical recovery capabilities in dynamic drift ice is cited repeatedly in the published literature (Abdelnour and Comfort 2001, Dickens and Buist 1999, Fingas 2004). A 2004 report prepared for the Prince William Sound Oil Spill Recovery Institute and the US Arctic Research Commission (Dickins 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.”

LORI brush drum skimmer



MORICE brush drum skimmer



Lifting grading belt

Figure 3-10: Components of MORICE mechanical recovery system (Jensen and Mullin 2002)

3.2.3 Mechanical Recovery Systems Designed for Use in Dynamic Ice

In the 1970s, a number of studies investigated the challenges of spill response in ice conditions (Jensen and Mullin 2003). During the 1980s, a brainstorming session prompted a series of studies conducted under the auspices of the Canadian Environmental Studies Revolving Funds to consider new technologies for use in responding to oil spills in ice-infested waters. (S.L. Ross 1986, Abdelnour *et al.* 1986). In Norway, major research and development efforts occurred during the late 1980s through the mid 1990s, culminating in a large field trial in the Barents sea MIZ in 1993.

Much of the early work in mechanical involved adapting open water spill response equipment for use in ice-infested waters. Over the past several decades, researchers have continued to examine existing technologies to test their potential application in ice-infested waters, while also considering new or modified equipment. Because dynamic drift ice directly interferes with both containment and recovery, much of the research has focused on technologies to move the ice away from areas where collection and recovery are taking place.

3.2.3.1 MORICE

In 1995, a joint research effort was initiated by a group of oil companies, spill response organizations, consultants, and regulatory agencies in an attempt to design a mechanical recovery system for use in marine ice conditions. The Mechanical Oil Recovery in Ice-Infested Waters (MORICE) project was conducted in six phases from 1995 through 2002. The outcome of this study was the development of ice processing and recovery equipment mounted onto a response platform (small vessel), which was tested in a large wave tank in simulated dynamic drift ice conditions (Jensen and Mullin 2003).

The MORICE project focused on a spill response in ice up to 70% coverage, with mild dynamic conditions and formation of brash and slush ice. The equipment was tested for oils with a range of viscosities. The major challenge was to develop equipment that could recover oil from within ice fields, and also develop ice cleaning methods. The basic concept involved a combination of recovering oil from within the ice using two different recovery systems, separating ice from oil (ice processing), and deflecting large pieces of ice to allow the unit to function. The component parts were developed separately and then combined into a single vessel-mounted unit (Jensen and Mullin 2003).

Figure 3-10 shows the main component parts of MORICE, which include: a lifting grading belt that is used to deflect ice away from the recovery unit and process the ice; a LORI® brush drum skimmer unit that was adapted with a screw auger to move ice to the rear of the unit; and a MORICE brush-drum recovery unit developed specifically for the project. These component parts were the result of significant trial-and-error and constant re-engineering to meet the demands of ice conditions.

The MORICE unit itself has not been brought to market; however, new skimmers reflect some of the lessons learned through MORICE (Mullin 2006). While 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 ice-infested water, particularly for large-scale oil spills. One skimming technology that has shown 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. Crane-mounted skimmers using similar technology are also available and marketed for arctic use. In general, the use of skimmers in ice is considered more appropriate for "batch" removals, focusing on small pockets of oil, than recovery of oil from a major blowout (BPXA 2003).

3.2.3.2 Oil deflection systems

Oil deflection systems use technologies such as air jet blowers, propeller wash, or pneumatic diversion booms, belts, or plates to redirect the flow of oil into a collection area while moving ice in a different direction (OSRI 2004).

Researchers in Finland have developed oil spill response devices for ice-infested waters that may be attached to the bow of a vessel and include a combination of ice-processing belts and skimming systems. One configuration uses a vibrating unit to create a flow field under the ice and channel oil toward the skimmer while diverting most ice pieces. The vibrating unit has been improved over time through a series of laboratory and field tests that began in 1997, with successive changes amounting to a reduction in the amount of oil that entered the recovery unit (Rytkonen *et al.* 2003). Earlier tests experimented with a perforated conveyor belt that moves the ice under the vessel while allowing water and oil to flow toward the skimmer unit (Rytkonen *et al.* 2000).

The Lamor Oil Ice Separator (LOIS) reflects the outcome of these studies and is now available on the market. The LOIS is installed on the side of a dedicated response vessel capable of operating in ice conditions. An oscillating ice grid washes the oil from ice chunks as they move along the grid, and separated oil is concentrated for recovery using a skimmer. The system is in use in Finland and available on the market.

Researchers at ExxonMobil are in the process of testing pneumatic diversion booms for use in dynamic ice. Figure 3-11 shows conceptual sketches of these booms, which would function similarly to other oil diversion devices by using water velocity to direct oil in one direction, toward recovery devices, and ice in another (OSRI 2004). Pneumatic air injection has also been tested as a response method to remove oil trapped under solid ice (Rytkonen *et al.* 2003).

Many of these ice deflection technologies have shown promise, and researchers continue to fine tune them, recognizing that additional research and development efforts are needed (Narita *et al.* 2001). Some research in this area has been proprietary and is not readily available in the public domain.

3.2.3.3 Ice Management Systems

Ice management systems have been used with some success to enhance mechanical recovery systems and in-situ burning in sea ice conditions. Ice management systems involve the use of ice booms or deflection methods to reduce the sea ice concentrations in areas where oil recovery or in-situ burning occurs.

Ice booms are affixed permanently in some locations to exclude sea or river ice from areas, facilitate navigation, or protect facilities or infrastructure. Abdelnour and Comfort (2001) report on the potential use of ice booms to exclude oil from areas where mechanical recovery or in-situ burning is taking place, concluding that ice booms towed in U-configuration against the flow of ice and ahead of the fire or oil boom-towing vessels may increase skimmer efficiency and/or increase burn efficiency. However, vessels towing the ice boom would generally require ice-breaking capability, or at least the ability to safely navigate in moderate to heavy ice conditions. Figure 3-12 shows a potential ice boom configuration for mechanical recovery.

Løset and Timko (1993) report on tests conducted in Norway to consider the use of boom to divert ice from around an offshore platform in the Barents Sea in order to facilitate oil recovery. The booms were towed upstream of the structure in ice conditions ranging from 50% to 100%. The tests showed that boom may be a feasible ice management system under certain conditions.

In addition to ice booms and the grading belts, other types of ice deflection devices have been utilized with varying degrees of success. Figure 3-13 shows a relatively simple ice deflection device: a metal grate positioned in front of a skimmer to deflect small pieces of ice away from the skimmer. Deflection devices must be carefully positioned so that they deflect ice, but not oil, from recovery devices. During 2000 offshore response trials in the Alaska Beaufort Sea, ice deflection grates were initially observed to deflect "oil" (simulated with popcorn) as well. The grate was raised slightly to avoid encounter with surface oil, which appeared to solve the problem of deflecting surface oil; however, the "oil" that adhered to deflected ice chunks was also deferred away from the skimmer (Robertson and DeCola 2001).

3.2.3.4 Response Vessels

Vessel capability is an important component of on-water oil spill response systems in sea ice conditions. Vessels towing ice boom must have sufficient operating capacities to handle the ice conditions and sufficient power to tow the boom against the force of the collected ice (Abdelnour and Comfort 2001, Robertson and DeCola 2001). The availability of vessels can be a limiting factor in many locations. Work boats traditionally used in oil spill response operations generally do not have ice-reinforced hulls. Conversely, larger, ice-breaking vessels may not be able to access nearshore areas due to shallow marine waters or fast ice. When shore fast ice is present, vessels that are anchored in shallow waters may become frozen in the ice and unavailable to respond to an offshore spill, even if ice conditions further offshore permit vessel operations. Vessels moored offshore would not face this problem.

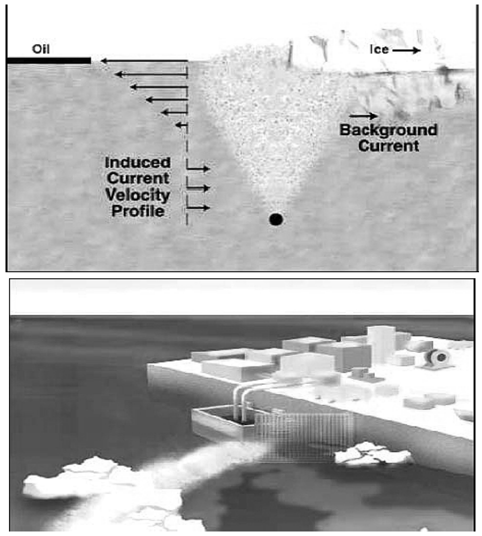


Figure 3-11: Pneumatic Diversion Boom Concept (ExxonMobil 2003 in OSRI 2004)

Multi-purpose vessels that can break ice and also provide spill response platforms and temporary storage are used in Finland and other arctic regions, and may prove useful to support mechanical recovery operations in dynamic ice conditions (SYKE 2004). Ice-breaking vessels may also be used for ice management by breaking up large ice floes and released trapped oil.

Ice deflection and ice management can be complicated; sometimes, ice management vessels may actually interfere with the spill response. During the 2000 Beaufort Sea response trials, as ice management vessels manoeuvred to deflect ice floes from recovery operations, their propeller wash often had the unintended result of deflecting oil away from the recovery operations, and/or pushing additional ice into the path of recovery operations. The propeller wash from ice management vessels was also observed to be problematic because it had the potential to mix oil into the water column, thereby reducing the potential for on-water recovery (Robertson and DeCola 2001).

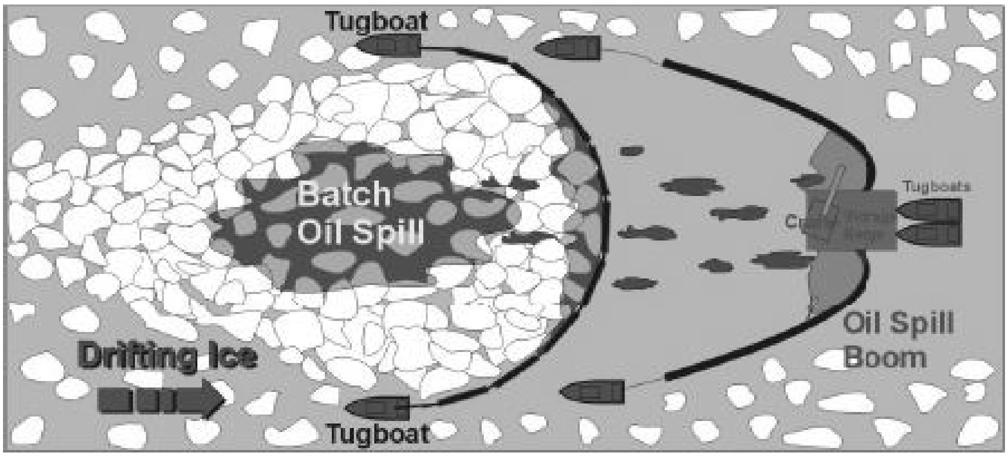


Figure 3-12: Potential use of ice boom to improve mechanical recovery in sea ice (Abdelnour and Comfort 2001)


Figure 3-13: Example of ice deflection grate (Photograph by K. Ballard, ADEC 2000)

3.2.3.4 Other Technologies

Narita *et al.* (2001) describe tests where they placed a specially designed oil recovery unit adjacent to a boomed area to recover oil in ice-infested waters. Within the boomed area, one or more work boats use a bow sweeper to corral the oil and ice and move it toward the recovery unit. Within the recovery unit, an air or water flow curtain is used to separate the surface oil from the ice. Oil is pushed toward the sides of the unit for recovery. Ice pieces remain in the centre of the unit where they are processed through water flushing, and "cleaned" ice is returned to the water (Figure 3-14).

Narita *et al.* (2001) propose that the recovery unit could be built to any size, based on average ice floe size. They conducted several tests using air bubbles and water jets to separate oil trapped under ice and found that both methods were effective under slightly different conditions, recommending the development of technologies that utilize both. A review of recently published literature does not reveal any additional development of this concept.

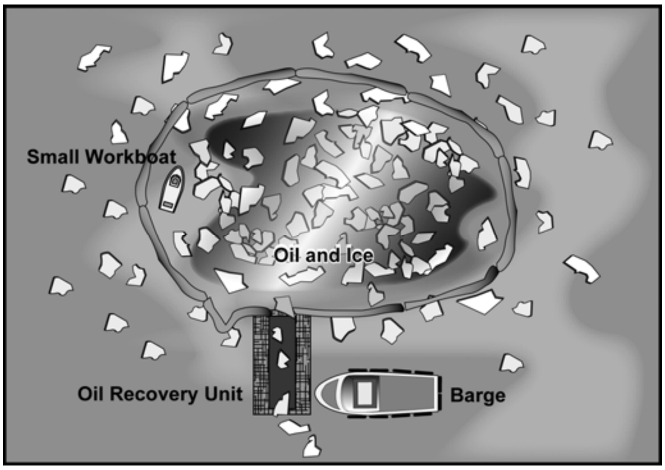


Figure 3-14: Configuration of oil/ice recovery operation (Narita *et al.* 2001)

3.3 In-Situ Burning

As researchers and spill responders have struggled with the limited effectiveness of mechanical recovery in sea ice conditions, they have simultaneously explored the potential use of in-situ burning to clean up oil spills in ice-infested waters. In-situ burning requires the containment of an oil slick to a sufficient thickness, ignition of the slick in a controlled burn, and removal of any remaining burn residue.

According to the US National Response Team, in-situ burning is considered to be a "viable response method" if certain slick thickness and environmental parameters can be met (NRT 1997a):

- The oil slick must be thick enough to ignite;
- Wind and wave conditions must be moderate;
- The oil must not have significantly emulsified; and
- The downwind emissions must be below threshold concentrations for sensitive populations.

3.3.1 Operational Considerations

In-situ burning of marine oil spills has some of the same operational requirements as mechanical recovery. First, spilled oil must be contained to the appropriate thickness to allow for ignition. Instead of recovering oil with a skimmer, as in mechanical recovery, in-situ burning ignites the oil slick. Burn residues must then be recovered.

3.3.1.1 Containment

As in mechanical recovery, oil containment for in-situ burning can be accomplished either with natural barriers (e.g. topographic features on land, snow berms, sea ice) or man-made booms. However, fire boom used for in-situ burning must be constructed of fire-resistant materials.

Most of the fire boom on the market today fits into one of three categories: traditional fabric boom, metal boom, and water-cooled boom. Traditional fabric boom is covered in a special coating to make it fire resistant. These booms are often comparatively inexpensive; however, they do not hold up as well under repeated burns.

Metal boom is usually constructed of stainless steel, and is exceptionally durable. While a stainless steel boom will hold up extremely well under repeated burns, these booms can be very cumbersome to handle and deploy. Because they are hard and inflexible, stainless steel booms do not mould to the ocean surface as flexible booms would, and therefore often do not contain oil as effectively, especially when they are towed through the water at speeds of 0.4 m/s or more. Stainless steel booms also require additional flotation, which is usually built in. Stainless steel booms are much heaver than conventional boom and require additional handling capabilities such as cranes and forklifts.

Water-cooled booms are considered to be the current state-of-the-art in fire boom technology. These fabric booms or boom blankets are kept cool throughout the burn by actively pumping fresh or sea water through the interior and cover of the boom. These booms combine the flexibility of a fabric boom with added durability (Stahovec and Urban 1999). However, they require a support vessel nearby to supply enough water to keep the boom saturated during burn operations.

Buist *et al.* (1999) report on efforts to engineer a fire boom that combines fabric and stainless steel by downsizing a traditional stainless steel boom to make a "burn pocket" that could be attached to any type of existing fire boom at the back of the "U" configuration, where the burn is typically concentrated (see Figure 3-14).

Air bubble and water-spray systems have been proposed as alternatives to fire boom; however, these systems are logistically complex and have a number of environmental and physical limitations (Allen 1999).

Response vessels generally tow fire boom in a U-shaped configuration that is also commonly used during mechanical response (Figure 3-4). However, rather than recovering the oil with skimmers and pumping the recovered oil into a series of storage units until it can be properly processed and disposed of, the contained oil is burned in place (NRT 1997a). Figure 3-15 shows typical in-situ burn operations on water.
Like conventional boom used in mechanical recovery, fire boom used in ice-infested waters must be sufficiently strong and towed by vessels with the capability to withstand the ice conditions.

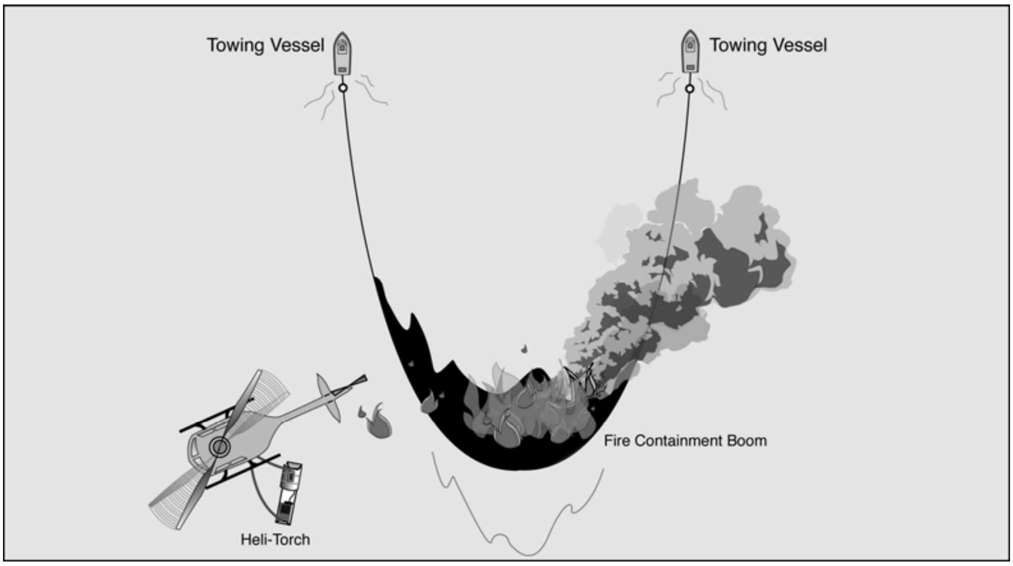


Figure 3-15: On-water in-situ burning (Nuka Research 2005, ACS 2003)

3.3.1.2 Ignition

Once the slick is contained at an appropriate thickness for burning, an ignition source is required to initiate the burn. In order to ignite, the slick must meet minimum thickness requirements, which vary depending upon the type of oil and degree of weathering.

In a 2001 study investigating the potential effectiveness of in-situ burning on a variety of crude oils, researchers found that various characteristics of the oils tested had measurable impacts on the likelihood that the oil could be burned. The researchers' test results indicated that oils with high API gravities (above 38º) tend to burn relatively easily, while those with API gravities below 20º will burn only under "optimal conditions." Their findings for oils with API gravities in the range of 20º - 35º indicated that the suitability of in-situ burning could not be predicted for these oils on the sole basis of their physical properties (McCourt and Buist 2001).

The 2001 tests did not include Sakhalin crude oils. The API gravity for Phase 1 oil from the Piltun-Astokhskoye field producing though the Vityaz production facility is 33.6 º (SEIC 2004), which would place it in the unpredictable range. Initial SEIC planning documents for Phase 2 indicate that the oil will burn; however, no published studies could be located to confirm this.

The degree of emulsification (percentage of water incorporated into the oil) also impacts in-situ burning options. Up until recently, emulsified oil was considered un-ignitable and therefore not a candidate for in-situ burning. However, recent work with emulsion breakers has demonstrated that it may be possible to burn emulsified oils under certain conditions. The burning of an oil emulsion involves a two-step process. The emulsion is first "broken," using chemical emulsion breakers that separate the water and oil and/or by applying heat to boil off the water content, so that a layer of un-emulsified oil will float on top of the emulsion slick where it will then be potentially ignitable. (Buist 1999). Chemical emulsion breakers also have toxicity risks that should be considered before applying them near environmentally sensitive areas (NRT 1997b).

A 2003 study that considers the windows of opportunity for in-situ burning on water points out that the interplay of a number of factors may ultimately determine whether a slick can be ignited. These include not only the physical and chemical properties of the oil, but the operational and technical requirements for in-situ burn operations (Nordvik *et al.* 2003).

To initiate the burn, the oil is ignited using one or more devices similar to a torch or flare, which may either be tossed into the oil slick by hand or dropped from a helicopter above the slick (Allen 1999). Ignition of the oil can be accomplished in a number of ways.

- Heli-torch systems are considered to be the current state-of-the-art for in-situ burn igniters. A Heli-torch is a device that is attached to a helicopter and from the air, releases burning gelled fuel onto the oil.

- Specially designed pyrotechnic devices (such as a Pyroid igniter or Dome igniter) can be released by hand from one of the ships towing the fire boom and allowed to float back to the oil, or it may be dropped by a helicopter onto the oil (Fingas 1999).

- Hand-held ignition systems can be relatively simple and effective, however a major downside of hand-held ignition systems is the fact that personnel must be in close proximity to the burning oil for deployment (EPA 1999).

3.3.1.3 Residue Recovery

A burn residue remains following an in-situ burn. Just as individual oil types burn with varying efficiency under different physical and environmental conditions, in-situ burn residues have differing characteristics and behaviour depending upon the chemical composition and physical properties of the parent oil, the state of weathering, and the oil slick thickness (Buist *et al.* 1997).

Burn residues may either sink or float. The residues sink only after they have cooled. Models of cooling rates predict that burn residues will reach ambient water temperature in less than 5 minutes for 3 mm-thick residues, and in 20-30 minutes for 7 mm-thick residues (SL Ross 1998). Recent research indicates that residues from burns of thicker slicks of heavier crude oils (both fresh and weathered) are more likely to sink in fresh or saltwater, once they have cooled to ambient temperatures, than are burn residues from lighter oils. 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).

The issue of whether in-situ burn residues sink or float is salient to determining how to remove the residue from the environment. If burn residue remains buoyant and it is practical to recover it before collecting and burning additional oil, the residue can be released to secondary containment booms. Whether recovered from secondary booms or the fire boom, the 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 labour intensive process (Figure 3-16).

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 following an in-situ burn of spilled oil. In this study, the results of small-scale burning experiments were used to develop correlations to predict burn residue densities for specific oils. The researchers found that, of 100 international crude oils tested, about half of the residues would tend to float, and the other half would tend to sink in seawater once the residue cooled to ambient temperatures. Generally, the study found that oils with an API gravity of less than 32º are more likely to generate sinking residues (API 2002).

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, thereby catching 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 published literature. The recovery of sunken in-situ burn residues in ice-infested waters has not been well studied.

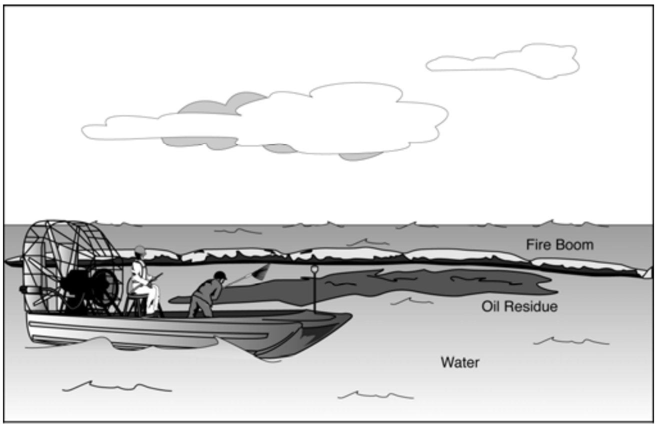


Figure 3-16: Recovery of floating in-situ burn residue (Nuka Research 2005, ACS 2003)

3.3.2 Environmental Considerations

The by-products of in-situ burning include air emissions 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.

<u>3.3.2.1 Emissions</u>

In-situ burning is distinguished from other spill response technologies by a number of factors, not least of which is the fact that burn operations yield a highly visible plume of dark smoke (Figure 3-17). This 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 in-situ burn emissions.

A number of studies have been performed to assess the chemical content of oil fire emissions, including the smoke plume, particulate matter precipitating from the smoke plume, combustion gases, unburned hydrocarbons, organic compounds produced during the burning process, soot particles, and the residue that remains at the burn site (Fingas *et al.* 2001a).

Beginning in 1991, a team of researchers from Environment Canada, the US Environmental Protection

Agency, and the US Coast Guard conducted a series of over 45 mesoscale burns to analyse the contents of emissions and residues resulting from the in-situ burning of crude oil and diesel. The researchers analysed burn emissions for the following components: particulates, poly-cyclic aromatic hydrocarbons (PAH), volatile organic compounds (VOC), dioxins and dibensofurans, carbonyls, carbon dioxide, carbon monoxide, sulphur dioxide, and other gases. They made a number of findings regarding safe distances and levels of concern for a standard burn size of 500m, which is consistent with the amount that would be contained in a typical boom (Fingas, Lambert, *et al.* 2001a, 2001b; Fingas, Lambert *et al.* 1999; Fingas, Ackerman, *et al.* 1999).

At ground level, particulate matter from crude oil burns exceeded occupational health criteria values close to the fire and under the plume; however, the researchers noted that particulate levels are probably not dangerous beyond 500 m from a crude oil burn (Fingas, Lambert, *et al.* 2001a, Fingas, Lambert *et al.* 2001b).

Figure 3-17: Smoke plumes generated during in-situ burn test (US MMS photograph, courtesy of J. Mullins 1991)

3.3.2.2 Effects on Surface Microlayer

The surface microlayer, approximately the upper millimetre of the water surface, 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 microalgae with species compositions distinct from the phytoplankton in the layers below (Shigenaka and Barnea 1993).

Surface microlayer organisms are vulnerable to impacts from oil slicks; however these impacts do not seem to be intensified by burning. Experimental data from a large offshore burn showed that water temperature was not increased during burning, despite the intense heat generated by the burn (Fingas *et al.* 1994). Another study found no significant differences in toxicity or petroleum hydrocarbon measurements among water samples associated with unburned oil, burning oil, and post-burn residues (Daykin *et al.* 1994).

To date, no published studies address the potential impact of in-situ burning on the surface microlayer in polynyas. The relationship between polynyas and WGW feeding activities is relevant to the consideration of a Sakhalin II oil spill.

3.3.2.3 Burn Residue

Physical properties of burn residues vary depending on burn efficiency and oil type. Efficient burns of heavy crude oils generate brittle, solid residues, while residues from efficient burns of other crude oils are described as semi-solid. Inefficient burns generate mixtures of unburned oil, burned residues, and soot that are sticky, taffy-like, or semi-liquid (NOAA 2002).

Laboratory studies performed on eight test oils (seven types of crude oil and automotive diesel fuel) indicate that the majority of the crude oil residues were composed of non-volatile compounds, primarily asphaltenes, high boiling point (HBP) aromatics, and resins. None of the crude oil residues contained any volatile compounds, and all of them contained some portion of medium volatility compounds (Buist *et al.* 1997).

Studies on the residues produced during a large offshore experimental burn in Newfoundland (NOBE) found that the burn residue was no more toxic than the oil itself. Bioassays with water from laboratory- and field-generated burn residues of Alberta Sweet Mix Blend showed little or no acute toxicity to sand dollars (sperm cell fertilization, larvae, and cytogenetics), oyster larvae, and inland silversides. Bioassays using NOBE burn residues showed no acute aquatic toxicity to fish (rainbow trout and three-spine stickleback) and sea urchin fertilization (Blenkinsopp *et al.* 1997). There is little published data regarding sublethal effects of burn residues, and no information regarding the potential impacts of burn resides to benthic-feeding whales.

While a number of scientific studies have confirmed that the residues that remain following in-situ burn 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).

Floating residues can be stranded much as floating oil slicks along shorelines or other coastal features; however, due to their thick consistency, residues 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).

Sunken residues can threaten benthic communities and can foul submerged fishing gear, adversely impacting 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 102,000 tonnes of oil was burned. The residues sank and were distributed over an area of the seabed approximately 140 square kilometres in size. These residues adversely affected local trawl fisheries because the fishermen feared they would foul their gear (Martinelli *et al.* 1995).

The ITOPF cites one example of an in-situ burn where the residue tainted fishing grounds (2002). "In the response to the spill from the *Honam Jade* (South Korea, 1983) crude oil was deliberately ignited. As a result, a dense residue formed which sank and seriously contaminated shellfish beds. When oil does sink to the sea bed and cause problems, the scope for recovering it is limited."

3.3.3 In-Situ Burning in Dynamic Ice Conditions

Numerous published articles and reports refer to the potential use of in-situ burning in dynamic ice conditions. The general consensus is that leads in broken and pack ice provide an opportunity to burn, because the ice acts as a natural containment barrier to the slick and the open water in the lead provides an ideal burn opportunity. Reduced efficiencies for mechanical recovery are also frequently cited as rationale for using in-situ burning in ice leads.

During the fall of 2002, a team of researchers from the MMS, ExxonMobil, and several other organizations conducted a series of mid-scale in-situ burn tests in sea ice at the ACS wave tank facility in Prudhoe Bay, Alaska. Forty-two mid-scale tests were conducted on four Alaska crude oils, both weathered and fresh. The main objective of these experiments was to develop guidelines for the use of in-situ burning in dynamic ice conditions (Buist 2002).

The Prudhoe Bay tests focused on identifying the limits to ignition and the most effective means of burning spilled oil in ice-infested waters, particularly in fields of dynamic drift ice subjected to wave action. Burn efficiencies during the trials ranged from 45% to over 80% and yielded the following guidelines for in-situ burning in brash or frazil ice (Buist *et al.* 2003):

- Minimum ignitable thickness for crude oil in brash or frazil ice is 1-2 mm, approximately double the requirement for open water.

- Minimum ignitable thickness for evaporated crude oil in brash or frazil ice is about 3 mm, and tends to be slightly higher than the requirement for open water but within the range for evaporated crude on open water if ignited with gasoline-gelled igniters.

- Burn rates in frazil ice are approximately half the calm water rate. Burn rates in brash ice are approximately one-quarter the calm water rate. Wave action slightly reduces the burn rate in open water, but the half/one-quarter rules seem to apply in waves as well.

- The residue remaining on pack ice in calm conditions is approximately 1.5 mm (1.5 times the residue in open water). The residue remaining on brash or frazil ice in waves is approximately 2 mm (double the residue in open water).

No Sakhalin crude oils were tested. The ANS crude oil, which had an API gravity of 32°, was closest to the 33.6° API gravity reported for Phase 1 Sakhalin crude. Results from tests on ANS crude showed 60% burn efficiency in ice and 45% efficiency in ice with waves. Burn residues were 1.2mm in ice, and 1.8mm in ice with waves. All tests involved fresh ANS crude; emulsified ANS was not tested (Buist *et al.* 2003).

Buist *et al.* conclude from the Prudhoe Bay tests that a 3 mm-thick slick of weathered crude oil in brash or frazil ice could be burned in-situ with removal efficiencies of approximately 50% in calm water and 33% in waves (Buist *et al.* 2003). Other studies have shown that, on average, slush ice slows burning by 0.45 mm/min and brash ice by 0.8 mm/min (Fingas 2004).

Research into the use of herding agents, chemicals used to improve slick thickness is ongoing (Evers 2006).

3.3.4 In-Situ Burning in Response to Oil Well Blowouts

In-situ burning has been proposed as a cleanup strategy for oil well blowouts where oil is deposited on the sea surface. However, it may prove challenging to ignite oil from a blowout, especially during sea ice conditions. Oil well blowouts often propel oil and gas into the air, releasing volatile hydrocarbons and significantly modifying the crude oil characteristics by decreasing the volatile component fraction of the crude oil, which reduces its ignitability. Unlike a spill from a ship, pipeline, or tank where the crude oil may pool around the source thickly enough to sustain a burn, an oil well blowout often disperses the oil far from the source creating a thin sheen of oil which will be difficult or impossible to ignite if ice impedes the ability to thicken the oil spill using conventional booming devices.

Ignition of the well blowout at the source prior to dissipation of the oil into the environment has been proposed as a containment and destruction method by some operators. This response technique is called “well ignition.” While extremely successful in destroying the hydrocarbons right at the well blowout, many operators are reluctant to ignite a well, since it may result in total destruction of the oil and gas platform or facility. The decision to ignite the well must be made early in the response to maximize its effectiveness.

Further studies are needed to evaluate whether in-situ burning can be considered an effective response method for an arctic well blowout.

3.3.5 Limits Imposed by Dynamic Ice Conditions

In-situ burning in temperate open water conditions has been reported to burn up to 98% of certain oils (Buist *et al.* 1994). Small-scale studies of in-situ burning certain crude oils in sea ice propose efficiency rates in the 33% to 50% range (Buist *et al.* 2003). However, in-situ burning has not been widely used, particularly in cold climate on-water spill response; therefore, 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 in open water (Fingas 2004, Buist *et al.* 2003). However, in-situ burning studies in slush ice showed efficiencies as high as 50% for weathered crude oils and 80% for fresh oil (Buist *et al.* 2003).

Like mechanical recovery, in-situ burning depends on the percentage of ice coverage. The major difference between the two techniques 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 60%, in-situ burning generally requires the use of manmade fire booms to contain the oil to the desired thickness. When ice conditions range from 30% to 60%, in-situ burn operations will face many of the same constraints as mechanical recovery, because of the challenges of deploying containment boom. Boom-towing vessels must be able to manoeuvre and position boom to contain the oil to the desired thickness. An ignition source must be deployed from a vessel or aircraft.

When ice coverage is above 60%, in-situ burning may be accomplished using the ice floes as natural containment. In this case, the ignition source will most probably be from an aircraft, unless ice-breaking or ice-reinforced vessels are available and capable of manoeuvring in the vicinity of the spill.

Ice conditions in the 30% to 60% range are considered to be the "most difficult from an in-situ burning perspective" (Evers 2006). In this range, natural containment by the ice is less likely, and containment boom deployment is generally not possible.

3.4 Dispersants

Dispersants are a group of chemicals sprayed or applied onto oil slicks to accelerate the process of natural dispersion. They are usually used in oil spill response when it is desirable to reduce the amount of floating oil to minimize damage to shorelines, wildlife, and other sensitive resources.

Dispersants are chemical mixtures containing 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). Oil droplets are surrounded by surfactant molecules and stabilized (IPIECA 1993). Dispersants promote the formation of tiny oil droplets in the water column and prevent the re-coalescence of droplets into slicks because of their surfactant content.

The surfactants in a dispersant are distributed throughout the oil by means of carrying agents. The solvent component of a dispersant is mainly used to dissolve the surfactant and additives to promote uniform application of the dispersant to an oil slick. Typical solvents include water, water-soluble hydroxyl compounds, or hydrocarbon solvents with low aromatic content. Additives are often included in dispersants to enhance the biodegradability of the dispersed oil (Fingas and Tennyson 1991, Brochu *et al.* 1987).

3.4.1 Dispersant Application Systems

Dispersant application requires spray nozzles, pumps, hoses, and a sufficient quantity of dispersant to achieve the target dosage (Figure 3-18). Application dosage is usually expressed as the ratio of dispersant to oil; 1:20 is a common target dosage for many commonly-used dispersants.

Vessels or aircraft are typical application platforms from which dispersants are sprayed onto an oil slick (Figure 3-19). Either fixed wing or rotary wing aircraft may be used to apply dispersants. Additional vessels or aircraft are often employed as spotters to direct the application process and monitor the effectiveness of the application.

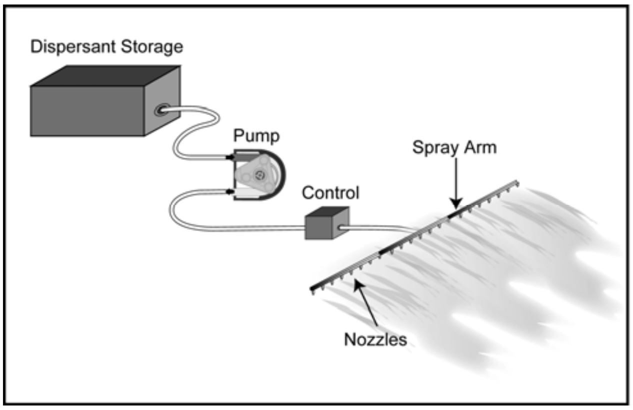


Figure 3-18: Dispersant application system components (Nuka Research 2005, ACS 2003)

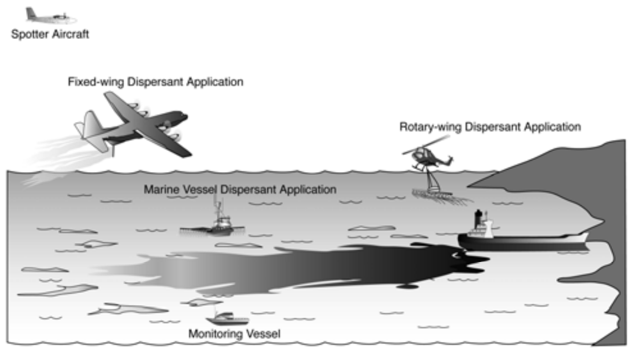


Figure 3-19: Dispersant application platforms (Nuka Research 2005)

3.4.2 Dispersant Use in Cold Water and Sea Ice

The use of dispersants in arctic and sub arctic waters presents a special set of considerations and concerns. Reduced water temperatures, variations in salinity, and the presence of sea ice can all impact dispersant effectiveness.

Researchers at the National Marine Fisheries Service Auke Bay Laboratory in Juneau, Alaska, US, 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% for fresh oil and less than 10% for weathered oil.

The Auke Bay 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%.” They caution, however, that these results are based on laboratory studies performed at low mixing energy (Moles *et al.* 2002). These results contradict an earlier study by SL Ross (1998), which concluded that Corexit 9527 should be reasonably effective on spills of Alaska North Slope crude in Prince William Sound or the Gulf of Alaska.

A series of wave tank experiments conducted in 2002-2003 indicated potentially higher effectiveness of dispersants in cold water. However, the protocols used in those experiments were brought into question in a recent US National Academies of Sciences report, which indicated that such practices as heating the oil may have compromised the validity of the results (OSB 2005). These trials were repeated in 2006 with revised protocols; the results have not yet been published.

A series of tank tests on dispersant effectiveness in ice-infested waters showed relatively high efficiency rates (Brown and Goodman 1996). More recent studies indicate that interactions between ice floes can enhance the dispersion process in high ice concentrations (Owens and Belore 2004; Belore 2003 in Dickins 2005). Researchers in Norway are considering whether the reduced rate of oil weathering in sea ice may extend the window of opportunity for dispersant use (Mølestad *et al.* 2005).

Dispersant toxicity is also an issue that weighs into response decision-making. 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 left behind following 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 gray whales, either directly or through uptake of contaminated food.

3.4.3 Limits Imposed by Dynamic Ice Conditions

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 recent review of dispersant use in oil spill response conducted by the US National Academies of Science recommends that additional studies are required to understand 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 ice-infested waters, including the potential use of ice-breaking vessels to add mixing energy (OSRI and ARC 2004).

Initial planning documents for Sakhalin II acknowledge the uncertainty surrounding dispersant use in the arctic and indicate that they will not be used as a primary response strategy for Phase 2 operations. "Without further validation and research, dispersants at this stage do not represent a primary oil-in-ice response option under freezing conditions." (Dickins 2005) SEIC has indicated that dispersants will never be used in the Piltun feeding area (WGW Workshop Report 2005).

3.5 Blowout Control

Oil spill response techniques usually focus on the process of removing, dispersing, or burning the oil once it has been released. Source control, which is the process of stopping the flow of oil from the spill source, is generally considered separately from the spill response. In spills from pipelines, tanks, and vessels, this assumption is often made because either the source has been controlled prior to initiation of oil spill response or a finite amount of oil is available to release. Recovery and removal are sometimes initiated simultaneously with source control operations for a pipeline, tank, or vessel spill. However, with an oil well blowout, source control plays a much more prominent role in the response because recovery operations around an oil well blowout can be extremely dangerous until the well is controlled.

Well blowouts may result in a continuous, ongoing release of oil for a period of days, weeks, or months. The volume of oil available for the oil spill will be a function of the oil and gas reservoir properties and the properties of the reservoir fluids. While not technically infinite, the ultimate volume of oil spilled may be orders of magnitude greater than a spill from a tanker, storage tank, or pipeline.

Blowout control is an important response strategy, as it would be the primary method to control and minimize the environmental impacts of a well blowout at a Sakhalin production platform.

3.5.1 Existing Technologies

A well blowout occurs when an uncontrolled flow of reservoir formation fluids is released to the surface. This can only happen if the wellbore hydrostatic overbalance is lost and the wellhead mounted blowout prevention system or the well casing on which it is mounted fails to contain the resultant pressure. (see Section 1.3.3).

When a blowout occurs source control measures are required to regain well control in order to stop the flow of oil or gas. Three basic approaches exist: additional surface control measures (well capping); ignition of the well blowout; and drilling a relief well.

3.5.1.1 Well Capping

Once the well has bypassed the blowout prevention (BOP) system and achieved an uncontrolled blowout state, the wellhead control equipment and the rig structure may suffer considerable damage. In this case, well capping may be used to control the well at the surface. Figure 3-20 shows a typical BOP system.

In order to cap and control a well, the well control specialist must be able to access the wellhead to either repair the BOP or remove the defective BOP to control the well pressure. Therefore one of the first challenges, and often the most time consuming, is to remove the rig structure and wellhead debris from around the well, while it is actively blowing out hydrocarbons and drilling muds and at risk of possible explosion. In some cases, the wellhead can be exposed by partially clearing away the damaged rig or offshore platform components; however, in some cases rig removal may also be required (Grace 2003).

Well capping requires specially trained personnel and specialized equipment to operate in these hazardous conditions. Compared to onshore well capping, controlling a blowout on an offshore platform presents additional challenges. In many cases, the cranes and heavily equipment aboard the platform will not be accessible to the well capping team, because it would be unsafe to place personnel on the platform with a well that is either blowing out hydrocarbons or is on fire.

Major fire fighting firms have crane hooks that work with large offshore cranes for debris clearing. Additional tools are generally custom fabricated at offshore sites using the machine shop and welding/fabricating capabilities of the work vessels to develop site specific solutions to the problems presented by the actual blowout damage. These activities require access to equipment, trained professionals, and significant time.

During well capping operations, a substantial amount of water is sprayed on the rig structure to cool the equipment and reduce the temperature of the working environment. In arctic operations, additional challenges are posed by water spray creating icy surfaces and structural loading.

During an oil well blowout, containment booms may be set around the work area, if safe, and recovery operations conducted. However, oil spill response operations are often limited to oil slicks that are located away from the blowout, so that well control operations are not impeded and oil spill response personnel are kept a safe distance away from the uncontrolled well.

Cutting away massive steel debris on large land rigs or offshore structures is sometimes required. Large fires will progressively weaken obstructing steel and at least partially expose the wellhead. If clearing is required, it can be done by various means such as bending or fatiguing the debris with a specialized vehicle and debris hook, using cables and winchers, cutting torches, using explosive charges, or cutting with high-pressure abrasive devices.

Once the debris is removed, a new wellhead must be installed to control the well. Well capping blowout control stacks are very heavy and must be raised into the air and lowered over the origin of the well blowout. The weight of this well capping blowout control stack must be sufficient to remain in place over a high pressure well blowout; therefore, it will also require a very large crane to move it into position. The well is then capped using a series of diversion and blowout control steps to secure the BOP over the well and control the well (Grace 2003). Figure 3-21 shows well capping operations.

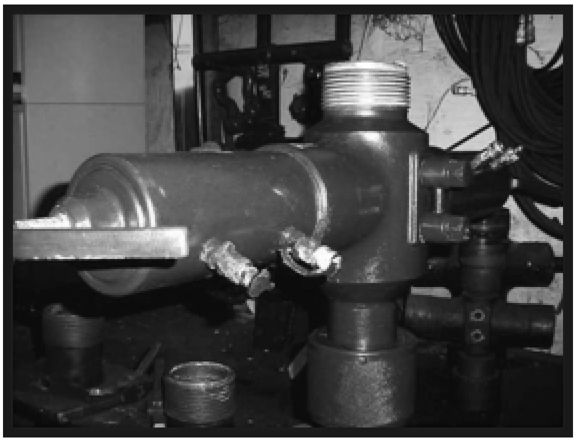


Figure 3-20: Blowout preventor

Figure 3-21: Well capping operations (on land, temperate)

3.5.1.2 Voluntary Well Ignition

Voluntary well ignition may be used during oil and gas blowouts, especially if there is a toxic component to the released hydrocarbons. The explosive limit of differing blowout flows varies with chemical composition.

In voluntary well ignition, the operator will introduce an ignition source to an area where volatile hydrocarbons are present. In spontaneous well ignition, an ignition source on or near the rig may inadvertently provide ignition (Paterson 1993).

Significant personnel and property safety issues are associated with well ignition during an ongoing (uncontrolled) well blowout, and operators are often reluctant to voluntarily ignite a well since it may result in complete loss of the well, rig, platform, or facility. Ignition of an oil well blowout on a major offshore platform would tremendously complicate control efforts and likely result in total platform loss. Difficult legal and insurance questions must be answered before an operator can determine its policy. Oil spill response personnel working around a well blowout will need intrinsically safe equipment, which does not produce a spark and provide an ignition source.

Once a well is ignited, seawater is often used to cool the area around the burn so that humans can access the well. In extreme cold, pumps and hoses may not work effectively. The introduction of large volumes of water to a spill area will make the response location a very icy and dangerous work platform.

3.5.1.3 Relief Well

A relief well may be drilled if a well does not bridge off naturally and cannot be controlled by well ignition or well capping. A relief well intercepts the subsurface wellbore of the out-of-control well to provide a path for pumping fluids in order to regain hydrostatic overbalance. A relief well is often not the first or sole choice to control the well because of the time it takes to mobilize a relief well rig into the area where the blowout is occurring.

If a rig is nearby, it may be possible to shut down drilling operations to aide in the blowout response. If there are no nearby rigs capable or willing to assist in the response operations, then it will take substantial time to move a second rig into the area. In the interim, other well control operations are usually initiated.

Once the rig is moved into the area, it still can take days to weeks to drill a well into the subsurface to a depth sufficient to intercept the wellbore that this actively blowing out. Once the wellbore is intercepted by the relief well, fluids are pumped into the well to control the blowout. Depending on the nature of the blowout these fluids may consistent of brine, drilling mud, or polymers; these fluids are often referred to as “kill fluids” because they serve to “kill” the well blowout. (Kelly and Flak 2006, Grace 1993)

3.5.2 Limits to Blowout Control in Sea Ice Conditions

International data on oil well blowouts in offshore arctic environments is not readily available in English reports or in readily accessible databases; thus, much of the information about blowout risks for offshore arctic wells is based on data compiled from the US oil development experience. In the US, there has not been a major oil spill in the offshore arctic waters of the Beaufort Sea, due in a large part to the fact that most of the oil development in Northern Alaska is located on land. In Alaska’s arctic, there have been 11 documented well control incidents during the period of 1977 to 2000 in which natural gas and/or drilling muds were released to the environment, which amounts to approximately 1.8 incidents per 1000 wells (Fairweather 2000).

In the US, data from temperate spills has been used in considering blowout risks in the arctic (MMS 1996). A 2003 study concluded that there is inadequate international information to accurately assess oil spill risk for Alaska’s arctic environment, and expressed concern about the use of temperate oil well drilling experience in area such as the Gulf of Mexico to characterise the risk of an oil spill in the arctic (SAC 2003).

Data is sparse and poorly compiled on the international experience with oil well blowout control in the arctic. Further study is needed in the area of both arctic well blowout risk and control methods for the arctic based on international and national experience to date.

Despite the information gaps regarding arctic well control practices, some conclusions can be drawn based on the known challenges of well control technologies such as well capping, well ignition, or relief well drilling in temperate or sub-arctic conditions, and extrapolating these challenges to how they may potentially be impacted by sea ice conditions and extreme cold.

All blowout control measures require time to mobilize and deploy the required equipment. A period of weeks or months may pass before well control is achieved. The presence of sea ice or adverse weather may extend the time required to control a well blowout.

Drilling a relief well is very difficult in sea ice conditions. For example, it took almost six months to mobilize a relief well rig and drill the relief well at a well blowout incident 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).

SL Ross completed a study that evaluated cleanup capabilities for a large blowout spill in the Alaska Beaufort Sea, concluding, "The presence of the ice and cold inhibits the spread and evaporation of the oil to some extent but often not enough to keep the oil sufficiently thick and fresh to allow for in-situ burning. The other approach, using conventional booms and skimmers, also has serious problems because the oil is often too thin and widespread for cleanup systems to operate efficiently, if at all, among the ice floes." (SL Ross *et al.* 1998)

The SL Ross report focuses primarily on cleanup options for oil that has been released during a blowout. It is equally important for offshore oil and gas operations to address how blowout control will be accomplished, especially in the presence of sea ice. Absent any published data regarding blowout control in sea ice conditions, the authors offer the following observations:

- Surface well control operations are complex and require specialized equipment and highly trained personnel.
- Offshore cranes, vessels and support equipment will be needed to support well capping operations.
- Well capping or well ignition operations may require access to large amounts of seawater for cooling and safety purposes.
- Sea ice may affect pump and hose operations. Freezing water may threaten safe vessel operation.
- The use of relief wells may be feasible for well blowouts in sea ice conditions, if drilling rigs are available and conditions allow for them to be transported through ice-infested waters.

A well blowout to ice-infested waters without effective well control could discharge a significant volume of oil that would likely overwhelm existing response capabilities in any arctic environment. A study commissioned by Alaska North Slope operators concludes that "mechanical containment and recovery techniques have limited application for a large spill [to ice-infested waters], especially one from an open-orifice blowout" (Dickens *et al.* 2000).

3.6 Review of Available Technologies for Oil Spill Response in Sea Ice Conditions

There is no one perfect technological solution to the challenges of responding to oil spills in ice-infested waters. Two types of technologies have shown some limited effectiveness in ice-infested waters: in-situ burning and mechanical recovery. Both are limited by ice conditions (percent coverage, thickness, presence of leads) and by operational and logistical issues, discussed further in Section 4.

Although dispersants are considered by some to hold promise for treating oil spills in ice-infested waters, further study is necessary to establish their applicability.

3.6.1 Mechanical Recovery

The following mechanical recovery devices and systems may have some effectiveness in dynamic ice conditions:

- Oleophilic skimmers seem to work better than other skimmer types in ice conditions because they limit the amount of water introduced into the skimming and storage units. Disc, drum, and rope mope skimmers can remove light and medium viscosity oils; brush and belt drum skimmers can collect heavy oils.

- Containment booms must be sufficiently durable to withstand the extra force from sea ice. Several types of large ocean boom have been demonstrated to be effective in ice conditions up to 30% coverage, although field trials have shown that ice coverage greater than 10% can be problematic for some systems.

- Ice booms may be effective in reducing the ice concentration to facilitate skimmer recovery operations. For effective deployment of ice booms, vessels must be able to safely operate in prevailing ice conditions.

- Other ice deflection devices may be used to prevent oil from interfering with skimmer operations; however, positioning is important to ensure that devices deflect ice but not oil.

- Ice treatment technologies that remove and treat oil-covered ice have shown some promise, although they present disposal challenges for treated ice and oily water.

- Multi-purpose vessels that can break ice and also provide spill response platforms and temporary storage may prove useful to support mechanical recovery operations in dynamic ice conditions.

- Pumps used in association with mechanical recovery must be able to pump viscous oils at cold temperatures.

- Most mechanical recovery equipment operates more effectively during spring break-up ice conditions than in fall freeze-up conditions. Fall ice conditions as low as 1% coverage have been demonstrated to limit the operation of some mechanical recovery systems.

3.6.2 In-Situ Burning

In-situ burning is considerably less expensive than mechanical recovery; it has been estimated to be five times cheaper than offshore recovery and 10 times cheaper than shoreline cleanup (Fingas 2004).

In-situ burning may be effective in ice-infested waters under the following conditions:

- The oil spill is not widely distributed and can be collected and contained to an adequate thickness for ignition.

- Volatile oil components have not been released due to dispersion via the blowout trajectory or by weathering, such that there are too few volatile components available to sustain a burn.

- Ice floes provide natural containment to maintain slick thickness necessary for ignition (2-3 mm).

- Fire booms can be deployed to maintain slick thickness necessary for ignition (2-3 mm). (Ice conditions can make boom deployment difficult or lead to boom failure.)

- Tracking and surveillance can be carried out from vessels or aircraft to direct ignition missions.

- Slicks can be accessed by vessel or aircraft to deploy ignition device.

Additional field studies that work through some of the practical considerations associated with in-situ burning in ice-infested waters – primarily tracking and ignition – will be useful in assessing the applicability of this technique. Response plans should address the significant safety considerations in using in-situ burning during an uncontrolled well blowout, due to the potential ignition of hydrocarbon vapours.

3.6.3 Dispersants

Research into the potential efficacy of dispersants in ice-infested waters is ongoing. Initial studies show that this may be a feasible response option, but response experts generally agree that additional study is needed. A major problem with dispersant use in ice-infested waters is the lack of mixing energy; however, several strategies have been offered to counter this effect.

Sakhalin II Phase 2 planning documents indicate that dispersants will not be a primary response strategy.

3.6.4 Response Decision-making

This report considers the technological, operational, and logistical issues associated with the three major types of oil spill response methods: mechanical recovery, in-situ burning, and dispersant use. The focus of this report is to consider the impact of sea ice on existing spill response technologies and the potential efficiency losses caused by dynamic ice conditions. However, the functionality of a response system is only one of several considerations in deciding how to mount an oil spill response.

Net environmental benefit analysis (NEBA) or net environmental and economic benefit analysis (NEEBA) is often applied by oil spill managers and contingency planners in selecting response technologies. Lunel and Baker (1999) propose that NEBA can be applied at three main levels, which correspond to the tiered approach to oil spill response: operational, tactical, and strategic.

Strategic NEBA applies to an oil slick at sea, focusing on the strategic decisions whether to use dispersants, in-situ burning, mechanical recovery at sea, no action, or allowing the oil to strand onshore and then focusing on shoreline removal. Tactical NEBA is used once the oil is in nearshore waters, when decisionmaking focuses on which areas of coastline to protect and which to "sacrifice." Operational NEBA is used by responders to determine whether to clean a particular area of coastline and the degree to which cleaning should occur. For a small spill, operational NEBA should suffice. However, for a major spill response, all three levels of NEBA may be applied at different stages of the response. By stratifying the NEBA in this way, different levels of impact can be considered during different stages of a response.

Lunel and Baker also describe a quantified approach to NEBA, which considers how different response methods affect the net oil budget and net environmental impacts that result.

Evaluating the conflict between environmental and socioeconomic or aesthetic concerns is extremely important in the spill response decisionmaking process. Baker (1995) related net environmental benefit analysis to often conflicting socioeconomic and ecological considerations and found that this presents several possible scenarios. There may be conflicts between ecological resources and socioeconomic interests, and also within each of these categories. For example, a clean up option may benefit one species while harming another, or may benefit one socioeconomic interest while hurting another. NEBA or NEEBA are commonly applied to consider the comparative impacts of dispersant use. Dispersant application to an offshore oil slick may reduce the quantity of oil that reaches shorelines, thus benefiting shoreline organisms and socioeconomic uses such as recreational beach use; however, the toxicity of the dispersant or dispersed oil may harm fishery resources.

Baker (1995) recommended that contingency planning should identify and attempt to resolve such areas of potential conflict *before* an oil spill. Lindstedt-Siva (1991) used ecological criteria to define environmental sensitivity on the grounds that "ecological impacts are both longer lasting, and once they have occurred, harder to repair than most other kinds of impacts (e.g., aesthetic, economic)."

Initial planning documents for Sakhalin II Phase 2 recommend the use of NEBA to select response options in an ice environment, recognizing that guidelines for the application of NEBA in ice environments do not yet exist (Dickins 2005).

4. The Dynamic Ice Response Gap

Compared to temperate, open water conditions, the ability to clean up oil spills in the presence of sea ice is extremely limited and conditional. Dynamic ice conditions present the most significant challenges to on-water spill response. There is very little commercially available equipment appropriate for use offshore in ice-infested waters. Actual experience responding to oil spills in the offshore arctic environment is extremely limited.

In this report, the authors use the term "response gap" to describe the gap between the upper limits of oil spill response systems and the potential on-scene conditions that may exist during an oil spill response. The response gap concept recognises that certain environmental conditions may severely limit or completely preclude oil spill response operations.

Sea ice and other cold climate conditions impose significant limitations on existing spill response technologies and systems. Several factors impact the response gap for spill response in sea ice – technological limits, cold climate efficiency losses, and safety limitations.

4.1 Impact of Sea Ice on Selection of Response Technologies

Mechanical recovery and in-situ burning are the two spill response methods considered applicable in ice-infested waters using existing technologies. Several published studies have considered the potential applicability of each technology in dynamic sea ice and drawn connections between the percentage of ice cover and the potential effectiveness of in-situ burning or mechanical recovery methods.

Figure 4-1 shows one estimate of the operational limits of oil spill response systems in ice-infested waters. It is important to recognise that these tables describe "expected" effectiveness only; there is little real-world data available to correlate these figures. As Singsaas and Reed (2006) note, "Few of these methods have actually been tested in ice-infested waters, so there are large uncertainties associated with the listed technologies." Singsaas and Reed also point out that the recovery capacities (amount of oil removed per unit time) of the response systems listed in Figure 4-1 vary widely.

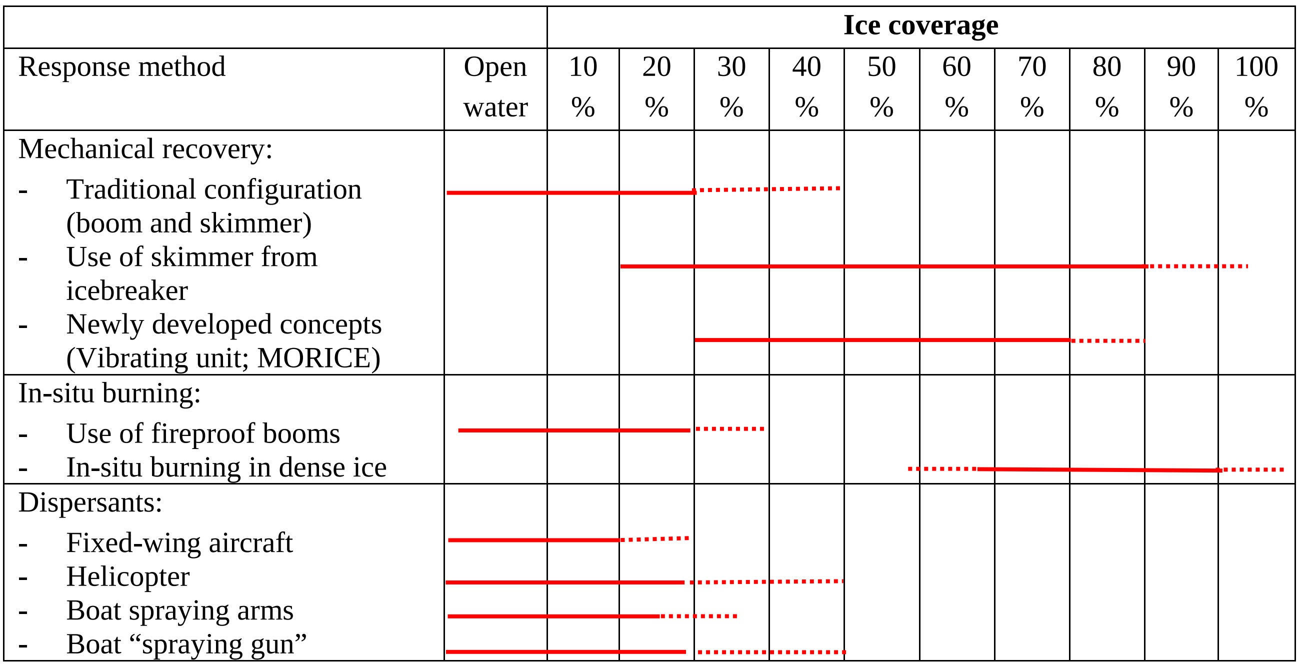


Figure 4-1: Indication of expected effectiveness of different response methods as a function of ice coverage (Evers et al, 2006).

Real-world experience deploying mechanical recovery equipment in ice-infested waters reveals that some systems may reach their operating limits well below the ice concentrations proposed in Figure 4-1 and other published studies. For example, the limit to mechanical recovery with containment booms and skimmers in ice-infested waters is estimated to be about 20%. However, the 2000 offshore response exercises in the Alaska Beaufort Sea demonstrated that the actual operating limits were closer to 10%, and that during fall freeze-up, ice conditions as low as 1% constituted the operating limit for a barge-based mechanical recovery system using conventional boom and skimmers In addition to ice coverage, the characteristics of the ice regime are an important determinant of response efficiency. The 2000 offshore exercises demonstrated that fall ice conditions (freeze-up) can be more challenging than spring break up (Robertson and DeCola 2001, NRC 2003). Therefore, 10% ice coverage in fall may pose different limits than 10% coverage in spring. These complexities make it difficult to develop meaningful guidelines for when certain technologies may or may not function.

Figure 4-1 suggests that the operating limits for in-situ burning are reached when ice conditions are in the 30% to 70% range. Above 60-70% ice coverage, in-situ burning is considered to have more promise due to the natural containment afforded by ice in combination with the reduced weathering of oil when ice is present. However, there is little real-world data to support these assumptions regarding the use of in-situ burning at high concentrations of broken ice.

The upper limit for dispersant use is also presumed to be 30% to 50% ice coverage. Again, these estimates are drawn primarily from small-scale trials with little correlation to actual spill responses.

4.2 Calculating Realistic Response Efficiencies

A response gap exists whenever activities that may cause an oil spill are conducted during times when the upper limits of available oil spill response systems are exceeded. In considering the operational limits to response technologies in broken ice, it is important to recognise the interplay of other environmental, logistical, and safety factors. Realistic maximum operating limits for response operations should incorporate all possible efficiency losses.

In addition to the technological limitations on oil spill response systems in sea ice conditions, efficiencies of mechanical recovery equipment such as skimmers and boom may be further reduced by the impacts of cold weather and ice on response personnel, vessel operations, and ancillary equipment such as pumps and anchor systems. Similarly, limited daylight and low visibility may complicate or preclude the operation of support vessels or aircraft.

4.2.1 Visibility and Daylight Limits

Arctic and sub arctic regions experience short days during the winter months. Interactions between ice, sea, and land may create fog banks that further reduce visibility. Heavily falling snow may cause white-outs. Any condition that reduces visibility may preclude or limit oil spill response operations, particularly air operations.

During the 2000 Alaska Beaufort Sea offshore response equipment trials, surveillance and ice spotting activities were limited by low visibility and coastal fog banks. Pilots required 0.6 km of visibility for fixed-wing aircraft surveillance operations, and 1.8 km visibility with a definite horizon to safely support helicopter operations. Helicopters supporting in-situ burning requirements require greater than 4 km visibility and a minimum 300 m ceiling (IT Alaska 2000).

Visibility requirements for safe vessel operations are generally lower than for aircraft, since vessels operate at a much lower speed. However, vessel operators must be able to spot ice floes. Likewise, responders must be able to see boom arrays and to visualize oil and ice in order to position and operate equipment. On-water spill response operations cannot be safely conducted in darkness or under heavy fog or white-out conditions.

An initial assessment by SEIC of oil spill response operations at Sakhalin II recognises the fact that limited daylight may impede a spill response: “In addition to the technical and safety issues involved with offshore and nearshore response under freezing conditions, limited daylight in combination with poor visibility could prove to be among the most important limitations for any offshore operation attempting to locate and recover oil in ice" (Dickins 2005). Experience with whale surveys near Sakhalin confirms that visibility limits can sometimes preclude or limit flight operations (Blokhin *et al.* 2004).

4.2.2 Cold Weather

In arctic and sub arctic regions where sea ice occurs, air temperatures often remain well below freezing for long periods of time. These extreme cold temperatures impact both personnel and equipment, and have the potential to significantly slow or even halt oil spill response operations.

Solsberg and Owen (2001) describe a training conducted on the Alaska North Slope in April 2000, during which time air temperatures ranged from -20º C to -40º C. "It was common practice to take shelter every 30 minutes or so as would be done during an actual spill response operation in such conditions." This observation illustrates one way in which cold temperatures may reduce the efficiency of spill response operations – response personnel must take frequent breaks in order to avoid hypothermia. Response personnel are also slowed by the bulk of additional cold-weather clothing.

Machinery is also vulnerable to extreme cold. Pumps and hoses are an integral part of most oil spill response systems, and without warming systems they are vulnerable to freeze-up. Vessel-based equipment and vessels themselves are vulnerable to icing when operating in the extreme cold, as sea spray freezes on exposed surfaces. Cold weather may pose a particular challenge to well control operations, which often involve the pumping of large quantities of sea water to cool well ignition.

Metal is also subject to brittle failure at subzero temperatures. Mechanical response devices designed for temperate oil spills must be redesigned with arctic grade metals, fittings, and seals reliable in extreme cold conditions.

4.2.3 Other Safety Considerations

During any spill response, safety is an overarching concern. On-water oil spill response operations are inherently risky, and the presence of sea ice adds to the potential for accidents.

Some organizations have recognised the need for extra diligence in ice-infested waters by identifying best practices for safe operations and spill prevention when sea ice is present. "Because of the inefficiency of the response technologies in ice-filled waters, transfers from vessel-to-vessel will require greater caution under extreme conditions." (Arctic Council 2002)

One way to improve safety is to ensure that all responders and vessel operators are appropriately trained and outfitted with proper safety equipment. An official with the Norwegian Pollution Control Authority reports that pollution prevention and contingency planning programs in Norway's arctic regions are challenged by the training requirements to ensure that vessel crew members are prepared to operate in a range of ice environments (Bjerkemo 2003).

4.2.4 Cumulative Impacts of Cold Weather Factors

The combined effect of winter conditions, sea ice, and the logistical constraints of responding to oil spills in remote areas can significantly reduce the effectiveness of spill response operations.

The March 2006 onshore pipeline spill on the Alaska North Slope provides a timely case study of the challenges associated with arctic spill response. The GC-2 oil transit line spilled an estimated 654 tonnes of crude oil through a hole approximately 0.6 cm, reportedly caused by internal corrosion of the pipeline. Because the spill was to frozen tundra, many of the factors that complicate on water oil spill cleanup were irrelevant. Yet, even in these more "favourable" conditions, the cold weather and snow cover complicated the response immensely (Figure 4-2).

Detection of the release was delayed due to the lack of visual access caused by snow cover. Once the release had been detected, it took responders three days to locate the spill source due to heavy snow cover (ADEC 2006a).

Air temperatures ranged to -30 º C, with wind chills to -50º C, and this extreme cold slowed cleanup operations considerably. Cleanup crews were limited to 25-minute exposure times, with longer interludes in a heated warm-up shelter (ADEC 2006b).

Figure 4-2: Cleanup operations for a pipeline spill to tundra on the Alaska North Slope (ADEC 2006)

4.3 Sakhalin II Dynamic Ice Response Gap

In the vicinity of the proposed Sakhalin II project, seasonal ice conditions are highly dynamic and are dominated by a constantly shifting pack ice with ice concentrations varying widely (see Section 2.1.5). A small fringe of landfast ice surrounds the island but is an unreliable platform for response operations. This combination of factors adds up to perhaps a worst case scenario for oil spill response operations, based on the technological, operational, and safety limits discussed earlier in this report.

SEIC background documents propose several possible oil spill response techniques for use in ice, noting that the window of opportunity to use many of these tactics may be limited to a few hours (Dickins 2005). This observation recognises that, during much of the Sakhalin ice season, the window of opportunity to apply oil spill countermeasures may be effectively closed.

4.3.1 Upper Limits of Response System

In considering the response gap for Sakhalin II, it is necessary first to identify the "upper limits" for the response systems in place. Upper limits may include ice conditions, visibility, wind, sea state, temperature, or other physical or environmental parameters.

The upper limits of a spill response system involve a dynamic interplay among multiple factors and the individual components of a response system. The degradation of spill response capability does not occur at a single point, nor is it necessarily linear in nature. For instance, mechanical response efficiency does not go from 100% to 0% as ice coverage increases from 29% to 30%. Likewise, ice coverage of 15% does not indicate that the response efficiency is one half that at 30%. The degradation curve is probably different for each environmental factor that impacts spill response. This further complicates the task of setting discrete operational limits for any one factor.

SEIC initial planning documents envision a combined in-situ burning and mechanical recovery strategy, with primary emphasis on in-situ burning, especially during winter ice conditions or for spills of moderate or large volumes (Dickins 2005). Mechanical recovery is feasible in ice conditions up to 30% coverage with ice management. In-situ burning is generally considered to be feasible in ice conditions less than 30% or more than 60-70%. Dispersants are not a primary response strategy at this time. Therefore, in the simplest of terms, ice conditions between 30% and 60% may represent the maximum response operating limit for spill response in ice-infested waters.

When ice conditions fall into the range of below 30% or above 60% coverage, a number of other conditions must be met in order for an in-situ burning or mechanical recovery response to be mounted. Wind and wave conditions must be suitable for the planned operations. The *Field Guide for Oil Spill Response in Arctic Waters* (Owens *et al.* 1998) recommends that wind speeds above 10 m/s and wave heights above 2 m are the maximum operating limit for both in-situ burning and mechanical recovery in open water conditions, although the limits for dynamic ice conditions may be greater or less. For this discussion, presuming that 10 m/s wind speed and 2 m wave height are the maximum limit for spill response in ice-infested waters, the maximum response operating limit occurs when ice conditions are between 30% and 60% **or** wind speeds exceed 10 m/s **or** wave height exceeds 2 m. As additional factors are considered, the response gap widens.

For in-situ burning operations in over 60% ice coverage, responders must be able to access the pooled oil with an ignition source before the oil weathers or spreads beyond the point where it is ignitable. This requires either ice-capable vessels or, more likely, air operations to ignite pooled oil. Sufficient aircraft must be available and ready to fly ignition missions before the window of opportunity closes. Visibility conditions must be sufficient for aircraft to operate at low altitudes. Wind speeds and sea state must not exceed ignition limits (Fingas 2004).

The response gap at Sakhalin II or other offshore oil and gas operations could be quantified by comparing historical climatic data against a set of upper limit parameters, such as ice condition, sea state, wind speed, air temperature, and visibility. While such an analysis is beyond the scope of this report, Table 4-1 lays the groundwork for calculating the response gap at Sakhalin, based on previously published studies that address weather-imposed limits on spill response (Owens *et al.* 1998, Fingas 2004, Evers 2006) and information in the SEIC background report on spill response in ice.

SEIC background documents address the potential use of fast ice response techniques during times when ice conditions are "sufficiently stable for personnel and light equipment." However, given the reported ice conditions at Sakhalin, the opportunities for fast ice response seem extremely limited. An SEIC background document recognises that safety considerations may dictate response operations, noting that in some cases, safety concerns will necessitate the "monitor and wait" approach (Dickins 2005).

4.3.2 Response Gap Considerations for Sakhalin II Oil Spill Response Planning

Most of the studies and reports on oil spill response systems in ice-infested waters presume a scenario where oil is released from a surface source and therefore available for surface removal. While this may be the case for a vessel spill, a well blowout at the surface or a platform spill, oil and gas operations also pose a significant risk of subsurface leaks from pipelines or wells.

This section considers how the spill source, ice conditions, and spill location may impact the applicability or effectiveness of spill response methods to a Sakhalin spill in ice-infested waters.

4.3.2.1 Well Blowouts

The proposed Sakhalin II Phase 2 operations include a number of potential oil spill scenarios. The most significant spill risk is probably from an uncontrolled well blowout. While such occurrences are rare, the consequences can be devastating. Initial SEIC planning documents suggest that in-situ burning would be the preferred response during a well blowout (Dickins 2005).

Well ignition may be a feasible source control measure; however, inadequate data is available to determine whether in-situ burning of pooled oil from a Sakhalin II well blowout would be feasible. Igniting oil from a blowout requires deposition patterns with sufficiently thick oil concentrations. Release of volatile hydrocarbons from the oil during dispersion may also impede ignition. In-situ burning may not be safe during a well blowout due to the ignition risk from hydrocarbon vapours.

Table 4-1. Upper limits for ice coverage, wind speed, and wave height that may be used to calculate Sakhalin II response gap

Parameter	Upper Limit for In-situ burning	Upper Limit for Mechanical Recovery	Conditions at Sakhalin
Ice coverage	**30% to 60%**	**30%**	**January-March ice is 20%-80%; breaking up April/May; freeze-up starts again in November-December**
Wind speed	**10 m/s**	**15 m/s**	**4-7 m/s average in winter; winter storms average 20-25 m/s (Nov, Dec, Feb)**
Wave height	**2 m**	**2 m**	**Maximum wave height may be 14 m or greater in open water. During ice season, maximum wave height ranges from 1-4 m, with higher waves (6-10 m) during winter storms.**

Thus far, no blowout modelling or flow rate estimates have been published for the Phase 2 production areas. Deposition models and flow rate data are essential to determine the worst case planning risk from a Sakhalin blowout. The blowout analysis for the Piltun PA-A and PA-B platforms provides a statistical analysis of the likelihood of a well blowout occurring (ESR 2006), but does not include any technical data, such as: the anticipated daily flow rate based on reservoir data; the potential blowout trajectory and deposition patterns; or the number of days required to effect well control, which would be used in conjunction with the maximum daily flow rate to calculate a worst case planning volume.

The response gap for well blowouts should also take into consideration the difficulties in responding to subsea releases, since well blowouts do not always occur at the sea surface. During a subsurface blowout, the released oil may emulsify before reaching the surface. Oil released from a subsurface blowout is also more likely to be trapped beneath broken or pack ice, which presents additional removal challenges (Mølestad *et al.* 2005).

The response challenges presented by a major well blowout in ice-infested waters are clear. Mechanical recovery of a large scale oil spill at Sakhalin II, or in any dynamic ice environment, is not feasible (Dickins *et al.* 2000, Dickins 2005). A study that evaluated cleanup capabilities to a large blowout spill in the

Alaska Beaufort Sea concluded that the containment effect of sea ice would not likely concentrate the deposited oil at a sufficient thickness to allow for in-situ burning (SL Ross *et al.* 1998). This leaves no effective means to clean up a large-scale oil well blowout to ice-infested waters.

4.3.2.2 Subsea Pipeline Releases

The recent GC-2 pipeline spill in Alaska highlighted the challenges to detecting, controlling, and cleaning up oil spills to land. Subsea pipeline releases can be even more difficult to detect, contain, and recover.

Subsea pipeline releases pose a similar set of challenges to subsurface blowouts, although the amount of oil released is generally smaller. A subsea pipeline release at Sakhalin II could occur near shore, where landfast ice may be present. If so, under ice recovery techniques may be applicable to remove trapped oil, if the oil is sufficiently thick to support response personnel. However, given the dynamic ice conditions at Sakhalin, such operations could be unsafe through most of the ice season.

SEIC proposes that in-situ burning may be used on “oil that has been exposed following the deliberate break up of ice at sea, or following the exposure of oil from within or below landfast ice” (Dickins 2005). This proposal relies on data that indicates slower weathering in sea ice, and thus assumes the oil will be available for recovery longer (Mølestad *et al.* 2005). However, there have been no documented studies that test the ignitability of oil that has been encapsulated in sea ice for extended periods of time.

4.3.2.3 Tanker and Storage Tank Spills to the Surface

The oil and LNG export terminal in the southern part of Sakhalin Island bears the most concentrated risk of an oil spill, because all of the oil and gas produced at all three platforms will ultimately be stored at and shipped through the export facility.

In the nearly 30-year history of oil production operations on the Alaska North Slope, where oil is transferred through a 1280 km pipeline to an export terminal in Valdez, Alaska, the single largest spill was from the tanker *Exxon Valdez*, caused in part by a shift in the tanker’s navigational course due to the presence of sea ice in the shipping lanes (Steiner 1999).

The magnitude of a potential tanker oil spill at Sakhalin is second only to the potential volume of an uncontrolled well blowout. Steiner (1999) considers the risk of an oil spill from Phase 1, which involved only a single production platform that does not operate during ice season, “[t]here are any number of scenarios for catastrophic oil spills from tankers off Sakhalin, including groundings or collisions caused by power or steering loss, navigational error, hull failure, fire/explosion, etc.” Presumably, these risks would be intensified for Phase 2 development, with the added complication of cleaning up an oil spill during ice season.

Depending upon the spill location, dynamic ice conditions could affect the response to a tanker or storage tank spill in a similar manner as described for other types of oil spills. Initial environmental assessment documents indicate that Aniva Bay, where the southern oil and LNG export terminal will be located, also experience dynamic drift ice conditions through much of the winter (SEIC 2005c). The presence of sea ice creates a significant spill risk to vessels both during loading operations and while in transit.

Figure 4-3: Photographs of T/V Seabulk Pride grounding in sea ice, Kenai, Alaska (Nuka Research 2006)

A recent ship grounding in Cook Inlet, Alaska highlights the risks posed by tanker operations in dynamic sea ice. In February 2006, the double-hulled *T/V Seabulk Pride* was struck by an ice floe while moored at a dock, causing the mooring line to part and the vessel to go adrift and then run aground (Figure 4-3). Six response tugs were involved in the effort to re-float the tanker and accompany her to a safe port (ADEC 2006c). This incident has caused the State of Alaska and the US Coast Guard to reconsider winter ice operating procedures in Cook Inlet, and has emphasized the need for preparedness in other arctic and sub arctic regions where sea ice is present at tanker loading facilities.

4.3.2.4 Piltun feeding area

In the oil spill response plan for Phase 1, SEIC indicates that dispersants will not be used to clean up oil spilled to the Piltun feeding area, and indicates that there will be some unspecified restrictions on in-situ burning as well (SEIC 2004). This commitment recognizes the unknown impacts of chemical dispersants or in-situ burn residues and emissions to the critical WGW nearshore feeding area. However, it also leaves only one option for responding to oil spilled in this area – mechanical recovery.

Under Phase 1, the Vityaz complex does not operate when sea ice is present. Therefore, the fact that mechanical recovery is not effective in ice conditions above 30% was not a concern during Phase 1, as any potential spill from Phase 1 would be to open water where mechanical recovery operations are more feasible. However, if Phase 2 operations commence year-round, the risk exists for an oil spill to impact the Piltun feeding area during the ice season. Response options would be limited to mechanical recovery, thus increasing the potential for oil to remain in the ice pack until spring thaw.

4.3.2.5 Seasonal Ice Conditions

Regardless of the spill source, oil spills that occur during fall freeze-up will generally present a greater challenge than those that occur during spring break-up, due to a combination of colder temperatures, potential for adverse weather, and limited daylight during the fall.

4.3.3 Implications of the Response Gap to the Critically Endangered Western North Pacific Gray Whale

As discussed in Section 2, oil that persists in the marine environment may negatively impact resident and migratory wildlife, including whales. The dynamic ice response gap at Sakhalin II means it is possible that part or all of an oil spill could go untreated throughout the winter ice season and impact wildlife and the environment for an extended period of time after the release.

The Sakhalin Island nearshore benthic environment is the summer feeding ground for the Western North Pacific gray whale. A major oil spill from Sakhalin that occurs during the summer months may directly oil the feeding grounds. An oil spill during the fall, winter, or spring ice seasons may remain largely untreated and become trapped in sea or landfast ice until thaw, at which point the oil would release and be available to directly impact the whales. Stranded shoreline oil may re-mobilize off beaches and impact the whales' feeding grounds. Weathered oil that entrains with sediments may sink and contaminate the benthic feeding grounds.

Pollution lingers in cold climates partly because bacteria that can break down oil thrive only briefly in the short summer season (AMAP 1998). This means that a major oil spill that impacts their feeding grounds could pose a risk to the WGW population over the course of several years or longer, which might bring the gray whale sub-species to the brink of extinction. The 1977 *Tsesis* oil spill in the Baltic Sea resulted in considerable deposition of oiled sediments on the sea floor. Several benthic organisms were observed to suffer effects ranging from mortality to reduced fecundity. Trophic transfers to bottom-feeding fish were noted (Elmgren *et al.* 1983).

The fact that spill response operations may be effectively precluded through the fall and winter ice season also means that the response to an oil spill that occurs during the fall or winter may actually be mounted in the summer, while Western North Pacific gray whales are present in the area. Noise and activity from spill response operations could be highly disruptive to the whales' feeding activities (ISRP 2005), and could also cause re-mobilization of oil from shorelines, thus increasing contamination risks.

An oil well blowout that occurs in the fall or winter could require months to control, as was the case with the Steelhead Platform in Cook Inlet, Alaska where a December blowout was not controlled until June of the following year. If this were to occur at Sakhalin, response operations might just be getting underway as the WGW arrived at their feeding grounds.

5. Conclusions and Recommendations

5.1 Challenges of Spill Response in Ice-infested Waters

The *Field Guide to Arctic Spill Response* describes a number of environmental and operational factors that combine to make arctic oil spill response operations especially challenging. Many of these same factors serve to intensify the potential environmental and wildlife impacts from oil spills in cold climates. It is essential that oil and gas operations be designed and regulated in a manner that addresses these unique response challenges and potentially devastating impacts (AMAP 1998, Owens *et al.* 1998).

- High intensity of habitat use during summer season
- Extreme seasonal ecological sensitivity variations
- Unique shore types
- Unique oceanographic and shoreline seasonal changes
- Seasonal ice conditions
- Slower weathering and longer persistence of spilled oil
- Remote logistical support
- Need to improvise response using available means until support equipment arrives
- Safety in cold, remote areas
- Low visibility due to fog and snow
- Frequency of storms and adverse weather
- Cold temperature effects on the efficiency of equipment and personnel
- Limited boat operations in ice-infested waters during transition periods, winter dynamic ice conditions
- On-ice operations in winter
- Seasonal daylight variability
- Need for aircraft support for response logistics, surveillance, and tracking

Because of these significant challenges and the high stakes of oil spills in cold climates, a robust oil spill planning and response infrastructure is needed to support oil development. Industry and government must participate in detailed environmental sensitivity assessments, coastal classifications, computer modelling, and regular training for response team members to ensure that an organized and timely response is possible. Spill response planning requires coordination among spill response organizations, industry, and government agencies (Glover and Dickins 1999, Goodman 2000).

A mature response system, including major equipment caches and a commitment to research and development, is especially important to respond to the challenges associated with spill response in ice-infested waters (Glover and Dickins 1999, Goodman 2000). Equipment maintenance and personnel training are equally important, as equipment that is not maintained or operated by skilled technicians is ineffective and potentially dangerous (Steen *et al.* 2003).

However, even in regions with well-developed oil spill response programs, large equipment caches, and trained responders on-site, there may be times when environmental conditions preclude any a spill response at all.

5.2 Acknowledging the Dynamic Ice Response Gap

"Oil spilled in broken-ice cannot be cleaned up effectively, and it is expected that whales would not avoid oil-fouled waters." (NRC 2003b)

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

"If oil is widely distributed throughout broken ice, no countermeasures methods might be practical." (Owens *et al.* 1998)

"No current cleanup methods remove more than a small fraction of oil spilled in marine waters, especially in the presence of broken ice." (NRC 2003b)

"Adverse weather conditions sometimes preclude any response at all and require a 'wait until thaw' approach." (Oskins and Bradley 2005)

"In some cases, safety concerns will necessitate the 'monitor and wait' approach rather than attempting a risky marine operation, which might also have a very limited chance of success." (Dickins 2005)

Existing oil spill response technologies do not work well in ice-infested waters. Mechanical recovery equipment fails at relatively low ice concentrations. Researchers continue to work toward improving response capabilities for ice-infested waters, and new technologies such as vessel-mounted oil/ice separators and bucket or arctic crane skimmers represent technological advances. However, the challenge comes in applying these technologies to a large-scale cleanup. In-situ burning, though considered by some to hold promise for arctic spill response, has not been proven in real-world dynamic ice conditions. At higher ice conditions, where in-situ is proposed as a favourable response option due to natural containment in ice, other logistical challenges ensue in trying to track the slicks, ignite them, and recover the residue.

At Sakhalin II, where sea ice conditions are highly dynamic and broken ice conditions can dominate for more than six months out of the year, the "no response" option may be the only option for half the year or longer.

During the 1990s, the State of Alaska acknowledged the response gap created by dynamic ice conditions in the Beaufort Sea during the permitting process for the BP NorthStar development, which was the first offshore (gravel island) oil production facility on the Alaska North Slope. The final permitting for the development included **seasonal drilling restrictions**, which prevent drilling into hydrocarbon-bearing reservoirs during the period from April through October, when dynamic drift ice (broken ice) may be present. These restrictions acknowledge the fact that responders will be unable to clean up an oil spill to ice-infested waters, and apply an operational restriction to reduce the risk of an oil spill during times when an effective response may not be possible.

Current operations at the Sakhalin II Phase 1 Vityaz complex are limited to seasonal drilling (during open water only) due to the inability for tankers to safely load oil during the ice season. However, with the development of the subsea pipeline and southern oil export terminal during Phase 2, year-round oil and gas operations are planned at Sakhalin.

5.3 Considerations for Sakhalin II

The Arctic Council (2002) recommends that oil and gas development in arctic regions incorporate the following practices to reduce oil spill risks and impacts:

1. Avoid adverse effects on climate and weather patterns

2. Avoid significant adverse effects on air and water quality

3. Avoid significant changes in the atmospheric, terrestrial (including aquatic), glacial, or marine environments in the Arctic

4. Avoid detrimental changes in the distribution, abundance or productivity of species or populations of species

5. Avoid further jeopardy to endangered or threatened species or populations of such species

6. Avoid degradation of, or substantial risk to, areas of biological, cultural, scientific, historic, aesthetic or wilderness significance

7. Avoid adverse effects on livelihoods, societies, cultures and traditional lifestyles for northern and indigenous peoples.

The fifth item above is particularly salient to the consideration of a dynamic ice response gap at Sakhalin II. The expansion of oil and gas exploration operations at Sakhalin increases the potential for a major oil spill in waters critical to an endangered whale sub-species and other wildlife. The highly dynamic ice conditions in the Sea of Okhotsk approximately six months of the year render ineffective most existing oil spill response technologies, particularly for a large-scale release. Other environmental conditions such as sea state, wind, and visibility limits have the potential to further narrow the window of opportunity for successful spill response. Cold weather will put an additional strain on response personnel and equipment. If a major oil spill occurs during the ice season and no response is possible, the WGW will be in very real jeopardy.

5.3.1 Limits to In-Situ Burning

In-situ burning has been presented by SEIC as a favoured option for response to a spill during ice season (Dickins 2005). Numerous other published studies focus on the potential use of in-situ burning in broken sea ice. However, this potential has yet to be demonstrated under real-world conditions.

While in-situ burning may be the best response option in ice-infested waters compared to other available technologies, it requires a narrow range of conditions that do not appear consistent with the prevailing weather at Sakhalin. Ice concentrations must be below 30% or above 60%; during most of the Sakhalin ice season, ice conditions are highly dynamic, with concentrations ranging from 20% to 80% (Dickins 2005).

Visibility must allow for air operations to spot contained slicks and possibly deploy heli-torches; fog is a persistent problem around Sakhalin. Wind and sea state must be light enough to support ignition; winter conditions often exceed ignition limits. Small vessels must be able to access the burn area for residue recovery, but vessel operations in and among higher concentrations of sea ice may be unsafe.

SEIC proposes that in-situ burning could be accomplished in small bursts during the narrow windows of opportunity (hours) afforded during freeze-up conditions (Dickins 2005). There are tremendous operational demands involved with conducting in-situ burning within such narrow timeframes; however, even if successful on only a small scale, in-situ burning does offer the opportunity to treat small pockets of oil and potentially reduce the spill impacts.

Studies have shown that the ignitability of crude oils with API gravity in the 20º - 35º range is unpredictable (McCourt and Buist 2001). The API gravity for crude oil from the Vityaz production facility is 33.6 º (SEIC 2004). SEIC documents state that the oil is ignitable (Dickins 2005); however, no published studies confirm this fact. There is a lack of data available regarding the fate and behaviour of Russian crude oils and crude oil products in ice-infested waters (Singsaas 2005).

5.3.2 Fate and Effect of Burn Residues

The American Petroleum Institute has determined that crude oils with densities greater than 0.864 g/cm^3 (or an API gravity less than 32 degrees) will produce burn residues that may sink (API 2004). The crude oil from Sakhalin falls into this category, with a density of 0.8695 g/cm^3.

Because of the challenges associated with operating small work boats in dynamic sea ice, in-situ burn residue removal may not be possible until spring melt, at which time the residues are likely to have sunk or spread, possibly impacting shorelines or benthos. The long term fate and effect of in-situ burn residues in the arctic environment is not well understood. These residues could pose a significant health risk to the Western North Pacific gray whales if ingested (ISRP 2005).

5.3.3 Impacts to Polynyas

SEIC proposes that the prevalence of polynyas in typical Sakhalin ice formations provides an excellent opportunity for in-situ burning (Dickins 2005). However, these same polynyas are a major source of nutrients in the arctic and are considered to be of vital importance to the entire marine food web, including marine mammals (Stirling 1997). Because in-situ burning may affect the surface microlayer, it is possible that in-situ burning in polynyas could have unforeseen food web impacts. Although the polynyas are present during ice season and the WGW feed in summer, the nutrient transfer from polynyas to benthic invertebrates may still be impacted by the presence of oil or burning oil. Further consideration should be given to this issue in the context of the Sakhalin development.

5.3.4 Blowout Control and Cleanup

Oil well blowouts have the potential to spill major quantities of oil. Blowout control is highly technical, complicated, and dangerous, and requires trained professionals and specialized equipment. Sea ice and cold weather further complicate the equation.

Oil well blowouts may continue uncontrolled for a period of months, resulting in an enormous spill volume to clean up. Surface well blowouts that widely disperse oil will likely create low volatility oil slicks not thick enough to ignite. There are no proven mechanical recovery methods for cleaning up a large-scale oil spill from an open orifice release in ice-infested waters (Dickins *et al.* 2000, Dickins 2005, SL Ross *et al.* 1998).

5.3.5 Subsurface Releases

Oil spills that originate below the water surface pose a particular response challenge when dynamic drift ice is present. Mechanical recovery may be possible from underneath ice if the ice is thick enough to support on-ice operations. In-situ burning may be very effective if the oil can be contained and emulsification is minimal. Dynamic ice conditions will complicate the process of cleaning up oil that is trapped beneath the ice.

5.3.6 Response Infrastructure

If Phase 2 proceeds as planned with year-round operations, the potential exists for an uncontrolled well blowout, tanker spill, or pipeline discharge to occur in ice-infested waters. The potential spill volume for a worst-case scenario from any of these sources could quickly overwhelm spill response capabilities, where large scale response operations may not be feasible due to ice conditions.

Significant response infrastructure is necessary to successfully mount large-scale oil spill response operations. Equipment stockpiles must be sufficient to manage a worst-case discharge. Planning must address the logistical challenges of storing, maintaining, mobilizing, and operating oil spill response equipment in ice-infested waters. Significant delays in mobilizing equipment or personnel to respond to an oil spill can severely reduce the response effectiveness.

5.3.7 Prevention Planning

The fact that oil spill response capabilities may be extremely limited under the prevailing ice conditions at Sakhalin II emphasizes the need for enhanced prevention planning. The best available technology should be applied to develop prevention systems for blowout prevention and control. Pipeline leak detection and corrosion control systems appropriate to the operating environment must be designed and maintained. Tanker operations should incorporate risk reduction measures that include structural measures, navigational procedures, and onboard operating procedures.

5.4 Response Gap Analysis

This report does not calculate the frequency or duration of the Sakhalin response gap; however, such analysis is recommended. SEIC planning documents acknowledge the important role that weather and ice conditions can play in determining the effectiveness of a spill response (Dickins 2005). Quantification of the Sakhalin II response gap would require detailed analysis of the specific environmental conditions at the project location. Such calculation would provide an extremely useful planning tool, shedding additional light on the number of days a year when ice conditions, wind, sea state, visibility, or cold temperatures may render oil spill response operations unsafe or ineffective. Such a calculation might also consider how certain spill scenarios – such as subsurface oil releases or uncontrolled oil well blowouts – exacerbate the response gap. The logical next step would be to implement mitigation and prevention measures to reduce or eliminate spill risks during times when a response may not be possible.

This report has identified several areas where additional work is necessary to address the dynamic ice response gap at Sakhalin.

- Complete a response gap analysis that calculates the number of days when environmental factors exceed the upper limit of oil spill response systems.
- Study the behaviour of Sakhalin crude oil burn residues and assess toxicity impacts to benthic species and potential for trophic transfer to whales through feeding. Consider potential for direct ingestion of sunken burn residues by whales.
- Examine the relationship between nutrient concentration in polynyas and the food web in the Piltun feeding area in order to assess potential impact of untreated or burned oil.
- Determine worst case scenario for oil well blowout and identify infrastructure needs to accomplish well control.
- Develop trajectory models for Sakhalin oil well blowouts to be used in assessing applicability of available cleanup technologies based on deposition patterns.
- Consider the response requirements for a worst case tanker spill to ice-infested waters.
- Continue with research and development efforts focused on improving oil spill clean up technologies in ice-infested waters, focusing on the development of response systems for use in large-scale recovery efforts.
- Conduct a net environmental benefit analysis for Sakhalin that considers the potential ecological impacts and tradeoffs associated with spill response options.

5.4 Conclusions

In a world economy where arctic and sub arctic oil and gas reserves are becoming increasingly targeted, the science of how spilled oil behaves and how it can be cleaned up in ice-infested waters is dominated by unknowns. This is especially true in the dynamic ice conditions that exist for half the year around Sakhalin II.

Considerable effort has been expended in recent years to improve the state-of-technology for oil spill response in the arctic, and particularly in ice-infested waters. Researchers are in the process of advancing technologies to track, contain, and recover oil spilled in ice-infested waters. As this research and development continues, breakthrough technologies may be identified to close or narrow the dynamic ice response gap. However, at this point in time, the challenge of applying existing response technologies to a catastrophic oil spill in ice-infested waters is significant. Available technologies may be able to clean up small pockets of oil; but no system has been developed to manage a large-scale cleanup in dynamic sea ice.

Despite the well-documented limitations of oil spill response technologies in ice-infested waters, arctic oil and gas development continues across the globe. Advancements in oil spill prevention technologies and enhanced vigilance by operators certainly help to reduce the risk of oil spills from arctic and sub arctic operations; however, the risk of a major oil spill will always exist. One study estimates the risk of a major pipeline release at 24% over the lifetime of a project, and a blowout at 3% (ISRP 2005). This risk is amplified in ice-infested waters by the response gap for offshore spill response.

The proximity of the proposed Sakhalin II oil and gas production operations to the summer feeding grounds of an endangered gray whale sub-species exacerbates the risks posed by the dynamic ice response gap. If a major blowout, pipeline release, or tanker spill were to occur during the six months when dynamic ice conditions prevail, the likelihood of an effective cleanup is extremely low. Most or all of the spilled oil could become bound up in the ice pack and re-released to the environment with spring melt. The potential for this oil to contaminate the whales' feeding grounds is very real; such contamination may persist for years, perhaps irreparably damaging an extremely vulnerable sub-species.

6. References

Abdelnour, R. & Comfort, G. (2001). Application of ice booms for oil spill cleanup in ice infested waters. Fleet Technology Limited. Kanata, Ontario. April.

Abdelnour, R., Johnstone, T., Howard, D., & Nisbett, V. (1986). Laboratory testing of an oil-skimming bow in broken ice. Environmental Studies Revolving Funds Report, No. 013. Ottawa, Canada. 60 pp.

ABS Project Development Team (2001). ABS brings experience, flexibility to Sakhalin II project offshore Russia. Offshore E-News. *http://www.eagle.org/prodserv/offshore-enews-3/sakhalin.html*

Alaska Clean Seas Technical Manual (2003). Alaska Clean Seas. Prudhoe Bay, Alaska.

Alaska Department of Environmental Conservation (ADEC). (2006a). Situation Report: GC-2 Oil Transit Line Release. SitRep #8. March 5.

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

Alaska Department of Environmental Conservation (ADEC). (2006c). Situation Report: T/V Seabulk Pride Grounding. SitRep #7. February 3.

Alexander's Gas and Oil Connections (AGOC). (2000). Shell's ATMOS pipe on line leak detection system to be marketed by DeTech. Vol 5, Issue 10. September 6.

Allen, A.A. (1999). New tools and technologies for controlled in-situ burning. *Proceedings of the Twenty-Second Arctic and Marine Oilspill Program Technical Seminar*. pp. 613-627.

American Petroleum Institute (API). (2004). In-situ burning: the fate of burned oil. Washington, D.C.: API Publication Number 4735.

Applied Analysis, Inc. (AAI). (2005). Spatial distribution of the fuel oil spill from the grounding of the M/V Selendang Ayu off the coast of Unalaska. *http://www.alaskaoceans.net/sao/aleutianoilspill.htm#photos*

Archer, J.S. and P.G. Wall (1986). *Petroleum Engineering, Principals and Practice*. Graham and Trotman, Ltd.

ATMOS International Limited (2002). Leak detection system brochure.

Baker, J.M. 1995. Net environmental benefit analysis for oil spill response. *Proceedings of the 1995 International Oil Spill Conference*: pp. 611-614.

Barron, M. (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.

Blenkinsopp, S., Sergy, G., Li, K., Fingas, M., Doe, K. & Wohlgeschaffen, G. (1997). Evaluation of the toxicity of the weathered crude oil used at the Newfoundland Offshore Burn Experiment (NOBE) and the resultant burn reside. *Proceedings of the Twentieth Arctic and Marine Oil Spill Program Technical Seminar*. pp. 677-684.

Blokhin, S.A., N.V. Doroshenko, and S.B. Yazvenko. 2004. Distribution, Abundance, and Movement Patterns of Western Gray Whales (*Eschrichtius robustus*) off the coast of Northeastern Sakhalin Island in June-December 2003 based on aerial survey data. Prepared for All-Russian Research Institute of Fisheries and Oceanography (VNIRO), Exxon Neftegaz Limited (ENL) and Sakhalin Energy Investment Company, Ltd. (SEIC), Vladivostok.

British Petroleum Exploration Alaska (BPXA). (2003). *Northstar Oil Discharge Prevention and Contingency Plan – Best Available Technology (Part 4)*. Revision 2, May.

Brochu, C.E., Pelletier, E., Caron, G. & Desnoyers, J.E.. (1987). Dispersion of crude oil in seawater: The role of synthetic surfactants. *Oil and Chemical Pollution.* Vol 3: pp. 257-279.

Brown, H.M. & Goodman, R.H. (1987). In situ burning of oil in ice infested waters. Technical Report Series. Environmental Studies Research Funds. National Energy Board. Canada.

Buist, I., Dickins, D., Majors, L., Linderman, K., Mullin, J. & Owens, C. (2003). Tests to determine the limits to in situ burning of thin oil slicks in brash and frazil ice. *Proceedings of the Twenty-sixth*

Arctic and Marine Oil Spill Program (AMOP) Technical Seminar. Environment Canada, Ottawa, ON. June 10-12.

Buist, I. (2002). SL Ross Environmental Research Ltd. Ottawa, Ontario, Canada. October 2. Personal communication with Elise DeCola.

Buist, I., Trudel, K., Morrison, J. & Aurand., D. (1997). Laboratory studies of the properties of in-situ burn residues. *Proceedings of the 1997 International Oil Spill Conference.* pp. 149-156.

Counterspill Research Inc. (1992). Evaluation of the foxtail skimmer in broken ice. Task Force on Oil Spill Preparedness. Technical Report Number 92-01. January.

Daykin, M., Aurand, D., Shigenaka, G., Wang, Z. & Tang., A (1994). Aquatic toxicity resulting from *in situ* burning of oil-on-water. *Proceedings of the Seventeenth Arctica and Marine Oil Spill Program Technical Seminar.* pp. 1165-1193.

D.F. Dickins Associates, Ltd. (2000). Detection and tracking of oil under ice. Minerals Management Service.

D.F. Dickins Associates Ltd., Vaudrey and Associates, Inc. And S.L. Ross Environmental Research Ltd. (2000). Oil spills in ice, Discussion Paper: A review of spill response, ice conditions, oil behaviour, and monitoring. Prepared for Alaska Clean Seas. December.

Dickins, D.F. (2005). Oil spill behaviour and oil spill response in ice conditions: a review. Volume II: Technical and Operational Review of Offshore Oil-in-Ice Response Strategies. Background Paper Number 4.2, Sakhalin Energy Investment Company, Ltd.

Dickins, D. & Buist, I. (1999). Countermeasures for ice-covered waters. *Pure Applied Chemistry* Vol. 71, No. 1. pp. 173-191.

EFA Technologies, Inc. (2002). Brochure.

Elmgren, R., Hansson, S., Larsson, U., Sundelin, B., & Boehm, P.D. (1983). The “Tsesis” oil spill: acute and long-term impact on the benthos. *Marine Biology*. Vol. 73, No. 1. Pp 51-65.

Environmental Protection Agency (1999). Understanding oil spills and spill response, chapter 5: wildlife and oil spills. Office of Emergency and Remedial Response.

Environmental Resources Management. (2003). Environmental impact assessment, Lunskoye seismic survey. Sakhalin Energy Investment Company, Ltd.

ESR Technology (2006). Sakhalin Piltun PA-A and PA-B Blowout Risk Estimate Review. Developed for Sakhalin Independent Review. 31 March.

Evers, Karl-Ulrich et al. (2004). State of the art report on oil weathering and on the effectiveness of response alternatives. ARCOP.

Evers, Karl-Ulrich et al. (2006). Oil spill contingency planning in the Arctic—Recommendations. Arctic Operational Platform (ARCOP).

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

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

Fingas, M.F. (1999). *In situ* burning of oil spills: A historical perspective. *In Situ Burning of Oil Spills Workshop Proceedings.* National Institute of Standards and Technology and US Minerals Management Service. New Orleans, Louisiana: November 2-4, 1998.

Fingas, M. and C. Brown. 2000. A review of the status of advanced technologies for the detection of oil in and within ice. Emergencies Science Division, Environment Canada.

Fingas, M. and C. Brown. 1997. Review of oil spill remote sensing. *Spill Science and Technology Bulletin*. Volume 4, Number 4.

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

Fingas, M.F., Lambert, P., Li, K., Wang, Z., Ackerman, F., Whiticar, S., Goldthorp, M., Schutz, S., Morganti, M., Turpin, R., Nadeau, R., Campagna, P., & Hiltabrand, R.. (2001a). Studies of emissions from oil fires. *Proceedings of the 2001 International Oil Spill Conference.* pp. 539-544.

Fingas, M.F., Lambert, P., Li, K., Wang, Z., Ackerman, F., Goldthorp, M., Turpin, R., Campagna, P., Nadeau, R., & Hiltabrand, R. (2001b). Studies of emissions from oil fires. *Proceedings of the*

Twenty-Fourth Arctic and Marine Oilspill Program Technical Seminar. pp. 767-823.

Fingas, M.F., Lambert, P., Li, K., Wang, Z., Ackerman, F., Goldthorp, M., Mullin, J., Schutz, S., Morganti, M., Turpin, R., Nadeau, R., Campagna, P. & Hiltabrand, R. (1999). Studies of emissions from oil fires. *Proceedings of the 1999 International Oil Spill Conference.* Article #133.

Fingas, M.F., Lambert, P., Li, K., Wang, Z., Nelson, R., Goldthorp, M., Turpin, R., Campagna, P., Schuetz, S., Morganti, M. & Hiltabrand, R. (1999). Studies of emissions from oil fires. *Proceedings of the Twenty-Second Arctic and Marine Oil Spill Program Technical Seminar.* pp. 467-518.

Fingas, M., Ackerman, F., Li, K., Lambert, P., Wang, Z., Bissonette, M., Campagna, P., Boileau, P., Laroche, N., Jokuty, P., Nelson, R., Turpin, R., Trespalacios, M., Halley, G., Belanger, J., Pare, J., Vanderkooy, N., Tennyson, E., D., & Hiltabrand, R. (1994). The Newfoundland Offshore Burn Experiment: NOBE preliminary results of emissions measurement. *Proceedings of the Seventeenth Arctic and Marine Oil Spill Program Technical Seminar*. pp. 1099-1164.

Fingas, M.F. & Tennyson, E.E. (1991). *A review of oil spill dispersants and their effectiveness*. Environment Canada and U.S. Minerals Management Service. 78 pp.

Fingas, M. (2006). Environment Canada. Ottawa, Ontario, Canada. February 28 – March 3. Personal communications with Elise DeCola.

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

Glover, N. & Dickins, D. (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*. Butterworth- Heinemann Publishers.

Gulec, I., and Holdway, D.A. (1997). Toxicity of dispersant, oil, and dispersed oil to two marine organisms. *Proceedings of the 1997 International Oil Spill Conference*: pp. 1,010-1,011.

Hobson, K. A., Fisk, A., Karnovsky, N., Holst, M., Gagnon, J.M. & Fortier, M. (2002). A stable isotope model for the North Water food web: implications fro evaluating trophodynamics and the flow of energy and contaminants. *Deep-Sea Research II 49.*

Independent Scientific Review Panel. (2005). Impacts of Sakhalin II phase 2 on Western North Pacific gray whales and related biodiversity.

International Petroleum Industry Environmental Conservation Association (IPIECA). (1993b). *Dispersants and Their Role in Oil Spill Response*. IPIECA Report Series. Vol. 5. 24 pp.

IT Alaska, Inc. (2000). Oil Spill Response Equipment Tests in the Alaska Beaufort Sea, Spring 2000. Prepared for Alaska Clean Seas. Unpublished.

International Tanker Owners' Pollution Federation (ITOPF). (2002). *Alternative Techniques for Oil Spill Response*. Accessed online at http://www.itopf.com/alternat.html. September 25, 2002.

Jensen, H.V. & Mullin, J. 2003. MORICE-new technology for mechanical oil recovery in ice infested waters. *Marine Pollution Bulletin v. 47*. pp. 453-369.

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

Lindstedt-Siva, J. 1987. Advance planning for dispersant use. *Proceedings of the 1987 Oil Spill Conference*: pp. 329-333.

Lindstrom, J.E., White, D.M. & Braddock, J.F. (1999). *Biodegradation of dispersed oil using Corexit 9500.* A report produced for the Alaska Department of Environmental Conservation Division of Spill Prevention and Response. 30 June.

Løset, S. & Timco, G.W. (1993). Laboratory testing of a flexible boom for ice management. *Journal of Offshore Mechanics and Arctic Engineering.* Vol. 115, no. 3, pp. 149-153.

Lunel, T., and J.M. Baker. 1999. Quantification of net environmental benefit for future oil spills. *Proceedings of the 1999 Oil Spill Conference*: paper ID# 210.

Martinelli, M., Luise, A., Tromellini, E., Sauer, T., Neff, J. & Douglas, G. (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.

McCourt, J. & Buist, I. (2001). Results of laboratory tests on the potential for using *in situ* burning on 17 crude oils. *Proceedings of the 2001 International Oil Spill Conference.* pp. 529-532.

Minerals Management Service (MMS). (1996). *Outer continental shelf oil and gas leasing program: 1997-2002* (draft). Minerals Management Service (Document 95-0061): U.S. Dept. of the Interior, Herndon, Virginia.

Moles, A., Holland, L., & Short, J. (2002). Effectiveness of Corexit 9527 and 9500 in dispersing fresh, weathered, and emulsion of Alaska North Slope crude oil under sub arctic conditions. *Spill Science and Technology Bulletin.* Volume 71, Nos 1/2: pp. 27-33.

Mølestad, M.O., Brandvik, P.J., Singsaas, I., & Daling, P.S. (2005). Oil spill contingency in ice-infested waters: present status and challenges. Presentation at INSOK Oil and Gas Developments in Arctic and Cold Regions Conference, Paris, October 20-21.

Mullin, J. (2006). Minerals Management Service. Leonardo, New Jersey. February 28 – March 2; March 15. Personal communications with Elise DeCola.

Munson, D. (2006). Alaska Department of Environmental Conservation. April 11. Personal communications with Elise DeCola.

Narita, S., Kanada, S. & Shimoda, H. (2001). A new oil-recovery method for broken ice conditions. *Proceedings of the Twenty-fourth Arctic and Marine Oilspill Program (AMOP) Technical Seminar.* June 12-14, 2001, Edmonton, Alberta, Canada.

National Oceanic and Atmospheric Administration (NOAA). (2002). In situ burning. Accessed online: *http://response.restoration.noaa.gov/oilaids/ISB/ISB.html.* October 30.

National Research Council (NRC). (1989). *Using oil dispersants on the sea.* The National Academies Press. Washington, DC.

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

National Research Council (NRC). (2003b). Board on Environmental Studies and Toxicology and Polar Research (BESTPR).*Cumulative environmental effects of oil and gas activities on Alaska's North Slope.* The National Academies Press. Washington, DC.

National Response Team (NRT) Science and Technology Committee. (1997a). *Fact Sheet: Site Safety Plans for Marine In Situ Burning Operations.* National Response Team Fact Sheet.

National Response Team (NRT) Science and Technology Committee. (1997b). *Fact Sheet: Emulsion Breakers and Inhibitors for Treating Oil Spills.* National Response Team Fact Sheet.

Nordvik, A.B., Champ, M.A. & Bittings, K.R. (2003). Estimating time windows for burning oil at sea: processes and factors. *Spill Science and Technology Bulletin.* Vol. 8 No. 4. pp. 347-359.

Nuka Research and Planning Group, LLC. (2005). Spill tactics for Alaska responders. Draft manual developed for Alaska Department of Environmental Conservation.

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

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

Owens, E.H., L.B. Solsberg, M.R. West and M. McGrath. 1998. Field guide for oil spill response in Arctic waters. Prepared for Emergency Prevention, Preparedness, and Response Working Group, Arctic Council.

Paterson, T.A. (1993). *Offshore Fire Safety.* Pennwell Publishers.

Peterson, Charles H., et al. (2003). Long-term ecosystem response to the Exxon Valdez oil spill. *Science 302.* 19 December.

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 U.S. Department of the Interior Minerals Management Services. OCS Study MMS 2004-038.

Prince William Sound Oil Spill Recovery Institute and U.S. Arctic Research Commission (OSRI and ARC). (2004). Advancing oil spill response in ice covered waters.

Reed, Mark et al. (1999). Oil spill modelling towards the close of the 20th century: overview of the state of the art. *Spill Science and Technology Bulletin.* Volume 5, Number 1.

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

Rytkonen, J., Sassi, J., & Mykkanen., E (2003). Recent oil recovery trial with ice in Finland. *Proceedings of the 26th Arctic and Marine Oil Spill Program.* Victoria, British Columbia, 10-12 June.

Rytkonen, J., Mykkanen, E. & Lampela, K. (2000). Novel oil recovery systems for ice conditions – Baltic experiences and demands for future. *Proceedings of International Oil & Ice Workshop 2000.* Anchorage, Alaska.

Sakhalin Energy Investment Company (SEIC). (2005). Marine mammal protection plan: a framework for mitigation and monitoring related to Sakhalin Energy oil and gas operations, Sakhalin Island, Russia.

Sakhalin Energy Investment Company (SEIC). (2005a) Overview of Sakhalin II project. *http://www.sakhalinenergy.com.*

Sakhalin Energy Investment Company (SEIC). (2005b). Public consultation and disclosure plan. Version 03.

Sakhalin Energy Investment Company (SEIC). (2005c). Oil Spill Response. Environmental Impact Assessment Addendum Chapter 2.

Sakhalin Energy Investment Company (SEIC). (2004). Synopsis of the Vityaz Oil Spill Response Plan Piltun-Astokhskoye Permit Area – Vityaz Complex. Web version.

Sayed, Mohamed et al. (1995). Spreading of crude petroleum in brash ice: effects of oil's physical properties and water current. *International Journal of Offshore and Polar Engineering.* Volume 5, Number 2. June.

Science Advisory Committee (SAC). (2003). *A review of oil spill risk estimated based on current offshore development technologies.* Report to North Slope Borough.

Short, J.W., Lindebert, M.R., Harris, P.M., Maselko, J.M., J.J. &. Rice, S.D. (2004). Estimate of oil persisting on the beaches of Prince William Sound 12 years after the Exxon Valdez oil spill. *Environmental Science and Technology.* Jan 1: 38(1): 19-25.

Singer, M.M., George, S., Lee, I., Jacobson, S., Weetman, L.L., Blondina, G., Tjeerdema, R.S. Aurand, D. & Sowby,.M.L. (1998). Effects of dispersant treatment on the acute aquatic toxicity of petroleum hydrocarbons. *Archives of Environmental Contamination and Toxicology.* Vol 34: 177-187.

SL 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, D.C., 50 pp.

S.L. Ross Environmental Research. (1986). Testing of an oil recovery concept for use in brash and mulched ice. Technical Report Series. Environmental Studies Research Funds. National Energy Board. Canada.

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

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

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

Stahovec, J.G. and R.W. Urban. 1999. Water-cooled, fire boom blanket, test and evaluation for system prototype development. *Proceedings of the Twenty-second Arctic and Marine Oil Spill Program Technical Seminar.* pp. 599-611.

Steen, A., deBettencourt, M., Pond, R., Julian, M., Salt, D. & Liebert, T. (2003). Global challenges to preparedness and response regimes. *Proceedings of the 2003 International Oil Spill Conference.*

Steiner, R. (1999). Oil spills: lessons from Alaska for Sakhalin. In *Economic Development and the Environment on the Sakhalin Offshore Oil and Gas Fields II.* Hokkaido University.

Stirling, I. (1997). The importance of polynyas, ice edges, and leads to marine mammals and birds. *Journal of Marine Systems 10.*

SYKE (Finnish Environment Institute). (2004). Fairway vessel *Seili* improves oil spill response capacity in the Gulf of Finland. Press release. February 19.

Tebeau, P.A. (1999). Alternative approaches to *in situ* burning operations. *In Situ Burning of Oil Spills Workshop Proceedings.* National Institute of Standards and Technology and US Minerals Management Service. New Orleans, Louisiana: November 2-4, 1998.

United States Coast Guard. 1998. Safety: We are the enemy. *Safety Alert.* *http://www.uscg.mil/hq/g-m/moa/docs/sa0998.html*

Wang, Z., Fingas, M., Landriault, M., Sigouin, L., Lambert, P., Turpin, R., Campagna, P. & Mullin, J. (1999). PAH distribution in the 1994 and 1997 Mobile burn products and determination of the diesel PAH destruction efficiencies. *Proceedings of the 1999 International Oil Spill Conference.* Article #459.

Western Gray Whale (WGW) Workshop Report (2005). Meeting held in Vancouver, BC, Canada: 17-19 September.

Wilson, D. & MacKay, D. (1987). The behaviour of oil in freezing situations. Environment Canada. Available from U.S. Department of Interior Marine Minerals Service.

Wolfe, M.F., Schwartz, G., Singaram, S., Mielbrecht, E., Tjeerdema, R. & Sowby, M. (1997). Influence of dispersants on trophic transfer of petroleum hydrocarbons in a marine food chain. *Proceedings of the 20th Arctic and Marine Oilspill Program Technical Seminar*: pp. 1,215-1,226.

World Meteorological Organization, 2005. *WMO sea-ice nomenclature*. Available online at *http://www.aari.nw.ru/gdsidb/xml/nomeclature.asp*

Yapa, P. & Weerasuriya, S. (1997). Spreading of oil spilled under broken floating ice. *Journal of Hydraulic Engineering.* August.

7. Acronyms

AAC	Alaska Administrative Code
ACS	Alaska Clean Seas
ADEC	Alaska Department of Environmental Conservation
AMAP	Arctic Marine Assessment Programme
AMOP	Arctic Marine Oilspill Program (Canada)
API	American Petroleum Institute
ARC	Arctic Research Commission (United States)
ARCOP	Arctic Operational Platform
ASV	Areas of special value
BAT	Best available technology
EPA	Environmental Protection Agency (United States)
EPPR	Emergency Prevention, Preparedness and Response (working group of Arctic Council)
GPS	Global positioning system
HBP	High boiling point
HELCOM	The Helsinki Commission
IR	Infrared
JIP	Joint Industry Program
MARPOL	International Convention for the Prevention of Pollution from Ships
MIZ	Marginal ice zone
MMS	Minerals Management Service (United States)
MORICE	Mechanical recovery of oil in ice-infested waters
NEBA	Net environmental benefit analysis
NEEBA	Net environmental and economic benefit analysis
NOAA	National Oceanic and Atmospheric Administration
NRT	National Response Team (United States)
OSB	Oil-skimming bow
OSB	Ocean Studies Board (United States)
OSRI	Oil Spill Recovery Institute
OSIR	Oil Spill Intelligence Report
OSR	Oil spill response
PAME	Protection of the Arctic Marine Environment (working group of Arctic Council)
PAH	Poly-cyclic aromatic hydrocarbon
QRA	Quantitative risk analysis
SEIC	Sakhalin Energy Investment Company
SERVS	Ship Escort Response Vessel System
SYKE	Finnish Environment Institute
US	United States
UV	Ultraviolet
VOC	Volatile organic compound
WWF	World Wide Fund for Nature

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WWF UK

James Leaton
Senior Policy Adviser
WWF - UK
Panda House,
Weyside Park,
Godalming,
Surrey,
GU7 1XR
Tel: +44 (0)1483 412513
Mob: +44 (0)7766 153974
Fax: +44 (0)1483 426409
email: jleaton@wwf.org.uk

WWF Germany

Volker Homes
Deputy Head Species
Conservation Section
WWF Germany and
TRAFFIC Europe-Germany
Rebstoecker Strasse 55
D-60326 Frankfurt,
Germany
Tel: +49 69 79144-183
Fax: +49 69 617221
email: homes@wwf.de

For further information on WWF's work on the Sakhalin II project go to:

www.panda.org/sakhalin

WWF International

Avenue du Mont-Blanc
1196 Gland
Switzerland

Tel: +41 22 364 9111

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