

GUIDE TO OIL SPILL RESPONSE IN SNOW AND ICE CONDITIONS IN THE ARCTIC

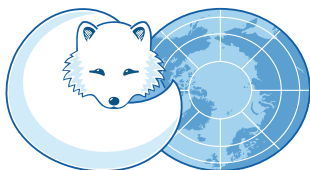


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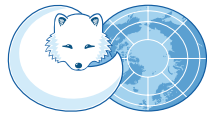
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Executive Summary

The objective of the Arctic version of the Guide is to identify and describe those aspects of planning and operations that are directly associated with a response to an Arctic oil spill in ice and snow conditions. Response strategies to deal with Arctic oil spills in summer open water conditions are not considered in the Guide.

The Guide encompasses a wide range of concepts and information that would be too unwieldy to condense in their entirety in this Executive Summary. Rather, the contents and key points are summarised where they are useful in a box at the beginning of each Part, Chapter and subsection of this Guide.

This Executive Summary is presented in two parts that reflect the very different, but linked, components of 1) Planning and Preparation for an incident, and 2) the Implementation of Response Strategies. These summary points are not presented in an order of importance: in fact, for the most part they are all important, as one component cannot be considered in isolation for planning, preparedness, and implementation.

One summary point deserves special attention for remote Arctic areas: the need to have a rigorous, scientifically defensible, streamlined process in place to rapidly assess the environmental trade-offs and process the necessary approvals related to the use of dispersants and *in situ* burning. The goal is to maximise all the available options in an emergency, including mechanical recovery, where they are appropriate and effective.

Giving responders the flexibility to rapidly select and apply the most effective and environmentally beneficial strategy is crucial to ensuring success of any spill response; linked

with the need for thorough contingency planning and drills in advance.

Planning and preparation

1. Oil spill response management, organisation, planning, decision and notification concepts and principles are not uniform worldwide, but frequently follow best practice guidelines (for example, ITOPF TIP #9). Planning, preparation and training for a response to oil spills in ice and snow typically have different goals and objectives to global recommended best practices depending on (a) the ice regime and ice cycle in a given area, and (b) the extent of supporting infrastructure (IP-IECA/OGP 2014).
2. Many Arctic areas have challenging weather conditions and low populations with limited infrastructure.
3. Multiple sources of oil spills in ice-affected areas include marine activities connected with oil and gas exploration and production, cargo vessels, research vessels, cruise ships, drilling operations and pipelines. Although still small in absolute numbers compared with other world trade routes (Suez, Panama, Straits of Malacca, etc.), the gradual increase in vessel traffic along the Northern Sea Route (NSR) and other Arctic areas, gives rise to an associated increase in spill risk. Assuming that the potential for spills from vessel accidents are directly related to traffic intensity, the Baltic Sea stands out with the highest risk

of any region covered in this Guide in terms of the numbers of vessels engaged in regular operations in ice.

4. Planning for the credible worst-case discharge is a primary requirement for new drilling applications but the frequency of such events is extremely remote compared to smaller Tier 1 or 2 spills. In 40 years of offshore drilling in Arctic waters, there has not been a Tier 3 incident. Of course, this is no indicator of a future where many more wells could be drilled in these areas, but it does point out that large spills occur infrequently. The probability of an extended loss of control event will continue to decrease with improved drilling technologies developed over the past decade; for example, well capping devices engineered following the Macondo incident in 2010 and enhanced BOPs in combination with devices such as the Alternative Well Kill System (AWKS). Areas in this Guide with the highest current concentration of offshore year-round oil production in ice include: Sakhalin Island, Alaska North Slope, and the Pechora Sea. All of the presently planned oil exploration programmes are designed and permitted for completion during the summer open water period and spills from those activities are unlikely to occur with ice present under normal circumstances.
5. When choosing a response strategy, key factors to be considered include local environmental conditions which, in areas such as the Baltic Sea, may lead to a regionally preferred response option of mechanical recovery rather than alternative response methods.
6. Sea ice structure, morphology and properties span a wide range of conditions, including ice formed in brackish low salinity water ice off major river deltas (e.g., Lena, Colville, Mackenzie), freshwater ice in Arctic rivers, and ice formed from very low salinity waters in the Baltic Sea. Differences in behaviour of oil in ice at different times in the ice cycle and in different areas affect every aspect of response planning and preparation. These include key characteristics such as: ice concentration or coverage, stability, drift rate, roughness, and timing of the spill relative to freeze-up or break-up. Planning response objectives, strategies, and tactics must reflect the timing of a response within the regional and local seasonal ice/snow cycle.
7. Ice often extends the time available to plan and execute an offshore response by containing, concentrating, and trapping the oil for long periods in a close to fresh state. At the same time, low temperatures, snow cover, and increased oil thickness can reduce the rate of evaporation and lead to longer persistence. While ice in sufficient concentrations may reduce the oil spreading and weathering rate, it will also greatly complicate the detection and mechanical recovery of spilled oil. Intermediate pack ice concentrations often referred “broken ice” may prove particularly challenging.
8. Landfast ice in many areas can act as an impenetrable barrier and protect the shoreline from direct oiling following an offshore spill for much of the year.
9. In terms of fate and behaviour, spills in ice are fundamentally different from spills in open water. Understanding this difference is critical for detection, trajectory analyses and strategic planning. Response techniques that work in open water and temperate regions may be ineffective or provide much reduced effectiveness in cold, snow, and ice.
10. The sensitivity and vulnerability of potential resources at risk vary significantly in time and space in areas with seasonal ice cover and snow. Many Arctic species are highly mobile or only present during the spring, summer, and fall: such as migratory waterfowl, bowhead and beluga whales. Fewer resources may be at risk when ice and snow are present through the winter.
11. The coastal environment is the breeding and nursery ground for many species

- upon which subsistence coastal inhabitants depend. From a human perspective, this coastal/nearshore zone is generally the most sensitive and vulnerable environment in the Arctic. Two primary objectives of regional and local response strategies are to prevent oil from reaching the coast and to protect those resources at risk. Responders should be aware that pelagic ecosystems and resources are critical in the Arctic and that response priorities and objectives should be developed using up-to-date “resource at risk” information, and in consultation with local experts.
12. Some shore processes and shore types are unique to the presence of ice and snow. Seasonal or year-round shore ice can be a dynamic process or a stable feature and the presence of ice and snow can completely alter the shore zone character.
 3. The availability of a scientifically defensible, streamlined process to rapidly assess the environmental trade-offs and process the necessary approvals related to the use of dispersants and *in situ* burning can provide the key to response success, especially in remote areas such as the Arctic. Maximizing the utilization of potentially limited operational windows, when the oil is still in a form amenable to recovery or removal, is an important objective of strategic and contingency planning.
 4. Detection of oil in ice and under snow is challenging and may require a mix of sensors and platforms including satellite, airborne, surface and subsea.
 5. Logistics limitations and sparse infrastructure in many remote areas with ice may favour response strategies built around air support.

Response and implementation

1. Although, in theory, there are several strategic tools in the responder toolkit, using these effectively in a real incident could be extremely challenging depending on many factors, such as: coping with the dynamic nature and unpredictability of ice; the remoteness and great distances that are often involved in responding in areas like the Arctic; the impacts of cold temperatures, ice and a harsh operating environment on response personnel and equipment; and the frequent lack of shore-side infrastructure and communications to support and sustain a major response effort.
2. Any significant ice concentrations can severely limit the effectiveness of mechanical containment and recovery in dealing with large spills. At the same time, the presence of ice can potentially increase the window of opportunity for successful burning and/or dispersant applications (that period when the oil remains unemulsified, thick and relatively fresh).
6. Operational and safety challenges posed by long periods of darkness and extreme temperatures, that are typical in marine and coastal environments with ice and snow, require a continuous process of risk assessment: safety of personnel is always paramount.
7. The selection of response strategies should be based on scientific principles embodied within the process of Net Environmental Benefit Analysis (NEBA): including the option of natural recovery. Responders also should be mindful that spills and response strategies can have significant effects on local and indigenous communities and subsistence users and that these concerns need to be considered in parallel with the NEBA.
8. Decisions on strategies for remote area oiled shoreline operations should focus on the use of *in situ* treatment options to minimise manpower requirements and waste generation.
9. Shoreline processes and shoreline character change with the seasons so that different strategies and tactics are necessary

at times and in places where ice and/or snow are present.

10. The application of proven response decision-making through some form of Unified Command and spill management

structure is no different for a spill in ice than in more temperate waters: the fundamental precepts and priorities remain the same. Subsistence issues may have a higher priority than in temperate zones.

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Glossary

ACS	Alaska Clean Seas
ADCP	Acoustic Doppler Current Profiler
AECO	Association of Arctic Expedition Cruise Operators
AIS	Automatic Identification System
ALARP	As Low As Reasonably Practicable
AMAP	Arctic Monitoring and Assessment Program
AMSA	Arctic Marine Shipping Assessment
API	American Petroleum Institute
ARRT	Alaska Regional Response Team
ART JIP	Arctic Response Technology Joint Industry Programme
ASTM	American Society for Testing and Materials
AUV	Autonomous Underwater Vehicles
AWKS	Alternative Well Kill System
BOEM	Bureau of Ocean Energy Management
BoHaSA	Behaviour of Oil and other Hazardous and Noxious Substances in Arctic waters
BOP	Blowout Preventer
BSEE	Bureau of Safety and Environmental Enforcement
CAA	Civil Aviation Authority
CDC	Centers for Disease Control and Prevention (USA)
CLC	International Convention on Civil Liability for Oil Pollution Damage (Civil Liability Convention)
CRREL	Cold Regions Research and Engineering Laboratory
DNR	Department of Natural Resources
DWT	Deadweight Tonnage
EPPR	Arctic Council Emergency Prevention, Preparedness and Response
FLIR	Forward Looking Infrared
FMCW	Frequency-Modulated Continuous Wave
FPSO	Floating Production, Storage and Offloading
GBS	Gravity Based Structures
GIRG	Global Industry Response Group
GPR	Ground Penetrating Radar
GPS	Global Positioning System
GOSR	Greenland Oil Spill Response
HBPF	High Boiling Point Fractions
HFO	Heavy Fuel Oil
HNS	Hazardous and Noxious Substances
HSVA	Hamburgische Schiffbau-Versuchsanstalt (Hamburg Ship Model Basin)
IAP	Incident Action Plan

IFO	Intermediate Fuel Oil
ILO	International Labour Organization
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IPIECA	International Petroleum Industry Environmental Conservation Association
IR	Infrared
ISB	In-Situ Burn
ITOPF	International Tanker Owners' Pollution Federation
JHA	Job Hazard Analysis
JIP	Joint Industry Programme
JPL	Jet Propulsion Laboratory
JSA	Job Safety Analysis
JTA	Job Tool Analysis
LNG	Liquefied Natural Gas
LOIS	Lamor Oil and Ice Separator
MCA	Maritime and Coastguard Agency (UK)
MIZ	Marginal Ice Zone
MMS	Minerals Management Service
MODIS	Moderate Resolution Imaging Spectroradiometer
MODU	Mobile Offshore Drilling Unit
MORICE	Mechanical Oil Recovery in Ice Infested Waters
MSC	Maritime Safety Committee
MSDS	Material Safety Data Sheet
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NCA	Norwegian Coastal Administration
NCOC	North Caspian Oil Company
NEB	Net Environmental Benefit
NEBA	Net Environmental Benefit Analysis
NFT	No Further Treatment
NMR	Nuclear Magnetic Resonance
NOAA	National Oceanic and Atmospheric Administration
NOBE	Newfoundland Oil Burn Experiment
NRC	National Research Council
NSIDC	National Snow and Ice Data Center
NSR	Northern Sea Route
NWP	Northwest Passage
O&G	Oil and Gas
OEL	Occupational Exposure Limit
OGP	International Association of Oil and Gas Producers
OMA	Oil-Mineral Aggregates
OSPRI	Oil Spill Preparedness Regional Initiative for Caspian, Black Sea and Central Eurasia
OSR	Oil Spill Response
OSRL	Oil Spill Response Limited
OSRO	Oil Spill Response Organisation
OSRP	Oil Spill Response Plan
OSRV	Oil Spill Response Vessel
OSV	Offshore Supply Vessel
PAH	Polycyclic Aromatic Hydrocarbons
PAME	Protection of the Arctic Marine Environment (Arctic Council)
PM	Particulate Matter

PPE	Personal Protective Equipment
PPT	Parts Per Thousand
ROV	Remotely Operated Underwater Vehicle
SAR	Synthetic Aperture Radar, OR Search and Recovery
SINTEF	Stiftelsen for industriell og teknisk forskning (Foundation for Scientific and Industrial Research)
SIR	Shoreline Inspection Report
SLAR	Side Looking Airborne Radar
SOLAS	Safety of Life at Sea
SOPEP	Shipboard Oil Pollution Emergency Plan
SOS	Shoreline Oiling Survey
STR	Shoreline Treatment Recommendation(s)
TPAH	Total Polycyclic Aromatic Hydrocarbons
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UNIS	University Centre in Svalbard
USAF	United States Air Force
USCG	United States Coast Guard
USGS	United State Geological Survey
UV/IR	Ultraviolet/Infrared
VEC	Valued Ecosystem Components
VOC	Volatile Organic Compound
WCD	Worst-Case Discharge
WMO	World Meteorological Organization



PART I – Introduction

Planning, preparation and response to an oil spill is a multi-faceted task that involves understanding a range of environmental issues related to the behaviour and fate of spilled oil and to the effects and recovery of habitats and species exposed to the oil. A response to spilled oil requires decisions on objectives, strategies, and priorities in the context of operational feasibility, practicality and safety. Adding the presence of ice or snow on water or in coastal areas adds a distinct and significant layer to this understanding and to the decision process.

The geographic scope of this Guide covers the region within the EPPR boundary

established by the Arctic Council members (Fig. 1-1) (http://www.grida.no/graphicslib/detail/boundaries-of-the-arctic-council-working-groups_8385) with the addition of the sub-Arctic areas of the Baltic Sea and the Sea of Okhotsk. The latter area covers the waters around Sakhalin Island and includes the active oil producing areas with platforms and marine pipelines off the east coast as well as the LNG terminal at Aniva Bay in the south and the marine oil export terminal on the Russian mainland at De-Kastri.

The many different forms of arctic ice and coastal environments present a wide range of possible operational scenarios that must



Figure 1-1. Arctic boundaries used by the different Arctic Council working groups.

be understood for planning, preparing and implementing an effective oil spill response with ice and snow present. The Guide does not deal with strategies needed to respond to open-water spills in the Arctic summer season.

The purpose of this Guide is to provide a better understanding to assist managers and decision makers in recognising and addressing key issues and potential response options at the strategic planning level. The Guide is:

- Generic,
- Strategic,
- Relevant for all areas with ice and snow that have a risk for oil spills, and

- Focuses on:
 - (a) ice and snow oiled from potential marine sources, as well as
 - (b) ice and snow in the coastal/marine environment oiled from potential terrestrial sources.

This Guide is not intended to serve as a stand-alone “how to” manual. The purpose is to complement existing field manuals that provide more technical step-by-step advice for managers and responders at the operations and tactics levels (Alaska Clean Seas, 2013; EPPR, 1998).

The primary topics covered by this Guide are:

PART II Developing Response Plans and the Decision Process	<ul style="list-style-type: none">• Chapter 1: Response Objectives• Chapter 2: Stages of a Response• Chapter 3: Feasibility: Opportunities and Constraints• Chapter 4: Net Environmental Benefit Analysis (NEBA)• Chapter 5: The Decision Process
PART III Key Planning and Response Elements	<ul style="list-style-type: none">• Chapter 1: Marine and Coastal Oil Spill Scenarios• Chapter 2: Arctic Coastal and Marine Ice Environments• Chapter 3: Coastal Processes and Shoreline Types in Ice- and Snow-Affected Coastal Regions• Chapter 4: Response Infrastructure and Logistics in Ice- and Snow-Affected Marine and Coastal Arctic Regions
PART IV Arctic Oil Spills in Ice and Snow: Behaviour, Fate and Effects	<ul style="list-style-type: none">• Chapter 1: Oil in Ice Fate and Behaviour• Chapter 2: The Effects of Spilled Oil in Ice- and Snow- Affected Marine and Coastal Environments
PART V Marine Strategies and Response Options for Oiled Ice and Snow	<ul style="list-style-type: none">• Chapter 1: Background and Introduction• Chapter 2: Detection, Delineation, Monitoring and Tracking• Chapter 3: Mechanical Containment and Recovery• Chapter 4: Dispersion and Oil Mineral Aggregates (OMA)• Chapter 5: Controlled Burning• Chapter 6: Summary of Marine Spill Response Effectiveness
PART VI Coastal Response in Ice and Snow	<ul style="list-style-type: none">• Chapter 1: Shoreline Assessment and Shoreline Treatment Decisions• Chapter 2: Shoreline Treatment Strategies and Options for Oiled Ice and Snow
PART VII Oil Spill Response Safety for Operations in Ice and Snow	<ul style="list-style-type: none">• Chapter 1: Principles of Safe Operations• Chapter 2: Risk Identification and Mitigation• Chapter 3: Job Safety Analysis



PART II – Developing Response Plans and the Decision Process

Chapter 1: Response Objectives
Chapter 2: Stages of a Response
Chapter 3: Feasibility: Opportunities and Constraints
Chapter 4: Net Environmental Benefit Analysis (NEBA)
Chapter 5: The Decision Process

- The principles of response planning and spill management are universal and no different for oil in snow and ice conditions.
- In an environment with static or dynamic ice and snow conditions, the response time lines may be extended if oil is contained, concentrated and trapped for long periods.
- In dynamic ice conditions, the extended response time line only applies if the oiled ice is tracked until the oil appears naturally on the surface or until vessels and crews can access the oil at some distance from the original spill site.
- A project response plan reflects the decisions developed by the spill management team to meet strategic and tactical objectives. Individual strategic plans are developed to implement a range of specific activities such as safety, air operations, communications, waste management, etc.
- Plans evolve as a response passes from a Reactive Phase, through a Planned Phase into the Completion Phase. In many instances, operational plans direct management and field activities over specific time periods (days or weeks).
- A Net Environmental Benefit Analysis (NEBA) is a strategic tool used by decision makers that formalises the evaluation and comparison of expected response effectiveness against the potential environmental impact of the oil and the response activities.
- The decision process typically involves the assessment of ever-changing information and data to develop and continuously update objectives and strategies.

Chapter II-1 Response Objectives

- A project response plan is based on a hierarchy of objectives: those which apply to the operations as a whole; strategic operational objectives; and tactical objectives of individual activities.
- Objectives may be site or geographic specific and/or be intended to reach a defined time line.
- Environmental conditions change continuously, especially in terms of weather, currents, and ice, so that information must be regularly updated and plans must be continuously revised to meet the response objectives. The natural containment provided by the ice may extend the time available to set objectives, plan, and implement a response.

One key element of preparedness is the development of contingency plans, or Oil Spill Response Plans (OSRPs), which may be geographic, site, or vessel specific (Table II-1.1).

There exists a wealth of guidance material for the preparation of vessel oil spill contingency plans, for example:

- IMO: <https://www.imo.org/OurWork/Environment/PollutionResponse/Inventoryofinformation/Pages/OilSpillContingencyPlanning.aspx>
- IPIECA/OGP Contingency Planning for Oil Spills on Water (2014)
- ITOPF <http://www.itopf.com/spill-response/contingency-planning/>
- United States Federal Register (Final Rule July 2013) <https://www.federalregister.gov/articles/2013/09/30/2013-22059/non-tank-vessel-response-plans-and-other-response-plan-requirements>

Notably, most if not all of this existing guidance material is concerned with the problem of accidental releases in open water rather than in ice-covered waters.

National government bodies, such as the Bureau of Safety and Environmental Enforcement (BSEE), US), National Energy Board

(Canada), Ministry of Industry and Mineral Resources (Greenland), and the Norwegian Petroleum Directorate, review and approve oil spill contingency plans required as a condition of granting permits to drill exploration wells or develop production facilities. In the event that the drilling location is affected by ice at any time during its operation, the plans must detail the specific response strategies proposed for dealing with spills in ice and demonstrate that necessary resources are on hand to meet what are often called response planning standards. Depending on the country or agency, these standards may specify that the operator contain all of the oil within a specified time frame. The OSRPs for offshore oil installations can be site specific and account for local environmental sensitivities and priorities. For most states, there is no generic template or guidance that can be readily used for arctic oil spill contingency planning in a drilling application, in contrast to many vessel plans that follow readily available templates.

The scope of each plan will vary although there are many common elements related to risk assessment, strategic policy, and operational procedures (ITOPF TIP #16). The objective of contingency plans is to be prepared in terms of:

TYPE OF CONTINGENCY PLAN	EXAMPLES
National or Regional	National Contingency Plan. Through cooperative agreements, regional plans may cover more than one jurisdiction: for example, the overarching Arctic Council Agreement on Cooperation on Marine Oil Pollution Preparedness and Response in the Arctic, as well as numerous bi-lateral agreements between individual Arctic nations with shared borders (Table III-1.1)
Site specific	Geographic specific: for example, oil handling terminal: storage tank site; pipeline route
Vessel specific	Apply to a ship wherever it is located

Table II-1.1 *Oil Spill Contingency Plans.*

- organisational structure and management of the response (ITOPF TIP #10),
- required notification procedures,
- identification of resources at risk, their sensitivity and vulnerability, and
- availability of equipment and resources.

Plans that cover geographic areas where ice and snow conditions are expected for some part or all of the year should consider how oil behaviour, resources at risk, response options and safety vary seasonally. Planning, preparation, and training for a response to oil in ice and snow have different goals and objectives depending on (a) the ice and snow regime and ice cycle in an area, (b) whether the area has a supporting infrastructure versus being in a remote region, and (c) locations and seasons with respect to subsistence hunting.

The implementation of an oil spill contingency plan at the time of an oil spill is only the first step in a response. No contingency plan can take into account the wide range of scenarios that include critical variables such as the specific location, oil type, oil volume, metocean conditions, and mobile resources at risk. Consequently, each incident requires the development of a response plan to address these very specific conditions. Typically, a response will have a hierarchy of objectives each of which may be addressed by a separate plan: those which apply to the operations as whole; strategic operational objectives; and tactical objectives of individual activities. In addition, response plans may have objectives that are site or geographic specific and/or be applicable to a defined time line, such as daily or weekly plans¹.

Typical objectives that apply to the response operation as a whole include:

- Protecting the health and safety of the public and the responders
- Source control
- Minimising the spread of the spilled oil by containment, recovery, or elimination
- Protecting sensitive locations
- Developing management, communications, operational, waste management and demobilisation plans

Within this framework, a spill management team then establishes geographic objectives, priorities and strategies and decides on the sequence of activities, based on resource protection or safety (priorities) and response options (feasibility and effectiveness).

Response to an oil spill requires continued adaptation to changing conditions. Oil movement, oil weathering, wind and sea state, tides, currents, and ice present a dynamic environment so that information must be regularly updated and plans must be continuously revised to meet the response objectives.

Chapter II-2 Stages of a Response

- A response typically follows three distinctly different phases: the emergency or REACTIVE phase; a PLANNED phase, and the COMPLETION Phase.
- In remote areas, with minimal infrastructure and long supply lines, a rapid or reactive phase may not be realistic or feasible.

For the most part, a response operation follows a sequence of three stages:

¹ An incident action plan, referred to as an “IAP” in some spill management systems, formally documents incident goals, operational period objectives, and the response strategy defined by incident command during response planning. An IAP contains general tactics to achieve goals and objectives within the overall strategy, while providing important information on event and response parameters. Equally important, the IAP

facilitates dissemination of critical information about the status of response assets themselves. Because incident parameters evolve, action plans must be revised on a regular basis (at least once per operational period) to maintain consistent, up-to-date guidance across the system.

Source: <http://www.phe.gov/Preparedness/planning/mscc/handbook/pages/appendixc.aspx>

1. Initial emergency or REACTIVE PHASE
 - Notifications
 - Many actions and activities follow pre-scribed scenarios
 - Information is gathered to define the scale and scope of the incident
 - First response objectives are defined
 - Several treatment or removal response activities can be most effective at this stage before oil weathers and spreads
2. PLANNED PHASE
 - Incident-specific decisions regarding priorities, objectives, strategies and tactics are developed based on information generated by detection, delineation and tracking surveys (at sea or on the coast)
 - Strategic and short-term plans for a range of response activities (safety, marine treatment and/or recovery operations, waste management, etc.) are developed
 - May involve monitoring and testing of response options
 - Response operations implement the plan(s) developed by the spill management team
 - Shoreline or on-land operations may involve strategic planning that is in the order of weeks to months whereas on-water operations involve a shorter time scale (days to weeks in many cases)
3. COMPLETION PHASE
 - The spill management team and the operations field teams demobilise as the site-specific or project response objectives are met.

Response cycles described in existing guides (e.g. IMO, ITOPE, IPIECA) were developed to define an open water spill in populated areas and presume that adequate resources are available to implement a first response. Although this may be valid for some sub-Arctic areas with regular winter shipping through

ice, such as the Baltic Sea, this presumption does not apply to many remote Arctic areas where winter logistics challenges and lack of infrastructure can severely delay or constrain the levels of response that are possible.

The reactive phase may not be realistic or feasible for an incident in a remote area, due to the lack of infrastructure and long supply lines. Response times to Arctic vessel accidents could extend to weeks or more in the case of reaching a remote accident site in the winter through consolidated ice, or even in a severe summer with high concentrations of drift ice affecting the ability of ice-capable support vessels to make progress. Except for spill sites close to shore within the landfast ice zone, surface vehicle access would not be possible over the ice, and air operations may be the only option. Such remote area response operations require extensive planning to ensure that the available resources are put to best use in a safe and effective manner that protects personnel while allowing a response to proceed.

In the rare cases where there is knowledge of a potential or impending accident, the planning phase can pre-empt the reactive phase. For example, the MV *Selendang Ayu* lost propulsion in December 2004 in the Bering Sea and drifted for 2 days before running aground and breaking in two (Annex E, Fig. E.3). During this short interval before the grounding, a Command Post was established at Dutch Harbor, one of the few ports in the southern Bering Sea. Response equipment was deployed from Dutch Harbor and began the transit towards the area by sea and air from other locations. In the case of spills such as this example occurring in remote areas at the worst time of the year (maximum darkness, most frequent storms), a response may stretch well into the next year. Although the reactive phase can be conducted immediately, subsequent phases are often best postponed until conditions on site are more favourable, for example, the following spring and summer.

Chapter II-3 Feasibility: Opportunities and Constraints

- One key to mounting an effective offshore marine response is to provide responders with access to the full suite of appropriate countermeasures without a protracted approvals process.
- Even with bi-lateral agreements, differences in approaches to oil spill response between neighbouring states could affect future efforts to deal effectively with a major trans-border incident.

Note: a number of Arctic States and bordering sub-Arctic areas affected by ice have different regulations or, in some cases, no clear guidelines governing the use of burning or dispersants. Alaskan state and federal agencies have embraced the concept of In Situ Burning (ISB) as a viable and effective tool that should be considered as one of the response options. Canadian authorities generally support the consideration of burning in an arctic setting but there are no clear guidelines that compare with those adopted in Alaska. To date, no Arctic nation has developed pre-approvals or streamlined decision processes to cover the use of dispersants in arctic waters. The current status of Arctic approvals for the use of ISB and dispersants among the different nation states is summarised in two reports released by the Arctic Response Technology JIP in 2013 (See References).

The development of a consistent and streamlined approach to permitting and approvals enables responders to act quickly and to apply the most appropriate countermeasure(s) within the often-limited operational window available to minimise environmental impact. A consistent regulatory approach is especially critical in areas with known trans-boundary spill risks, for example: Russia/Norway, USA/Canada, USA/Russia and Canada/Greenland (Denmark). Significant progress towards consistency was made in May 2013 with the signing of the Agreement on Cooperation on Marine Oil Pollution Preparedness and Response in the Arctic by Canada, Denmark, Finland, Iceland, Norway, the Russian Federation, Sweden, and the United States of America.

Timing is everything – being able to disperse while the oil is still dispersible, mechanically recover while the oil is still relatively unweathered, or burn while the oil is still ignitable, can significantly alter the outcome of a spill in ice (or open water) anywhere in the world.

An important key to overall success is flexibility: being able to use the best response tool in a timely manner that offers the greatest level of environmental protection. Responders in some parts of the world, especially the pristine Arctic, are bound, for example, by national policies governing the use of mechanical recovery versus burning versus dispersants. Mechanical containment and recovery is usually

granted a *de facto* approval while justifications for other strategies may require additional efforts to be considered for their use. One consequence is that options such as dispersants and burning may not be implemented in remote areas until it is too late to make a difference: for example, the oil is already onshore or too weathered. The NEBA process offers a pathway to package and present rigorous scientific arguments that can modify opinions, guide future regulations, and lead to better, more enlightened decision making in rapidly choosing and implementing the right response option for a given situation.

Developing response plans and selecting strategies for any given area where ice is present must take into account:

- First, the logistics capacity to deploy equipment and necessary resources; and
- Second, the available infrastructure to support the continued operation of those strategies in the field.

Having one without the other most likely will result in a response failure. For example, it may be possible to airfreight vast quantities of booms and skimmers into a remote airport but without the marine and shore-based infrastructure (work boats, ports, oily waste storage sites etc.) to support a mechanical recovery system, the response is not viable.

The issue of the need for self-sufficiency

requires careful consideration for remote areas where infrastructure is sparse and any spill site could be thousands or even tens of thousands of kilometres from a major staging base of oil spill equipment. No Arctic nations will permit an oil company to commence drilling without demonstrating that either the necessary response resources are nearby and available for rapid deployment, or proving that arrangements are made in advance to cascade resources quickly from outside the region in the event of a Tier 3 incident. However, the same provisions and assurances are not generally in place to an equivalent degree with vessels operating in remote areas.

This raises the question of what “self-sufficiency” would be like in these instances: for example, in regard to large cruise ships off West Greenland, tankers resupplying Arctic com-

munities, etc. Various workshops in the past have explored the idea of instituting a polar requirement for “self-help” in the event of vessel damage resulting in a spill. No consensus was reached in these discussions and the overall conclusion was that requiring crews to maintain competency in oil spill cleanup constituted a direct conflict with their priority roles in the immediate aftermath of an accident: that is, to maintain the safety of personnel, stabilise the vessel, and reduce or stop the outflow. There are other serious issues with the concept of vessel self-sufficiency in oil spill response, including the need to maintain equipment readiness in harsh environments, need for recurring competency training, and economic liability – that is, who will pay for equipment, ongoing maintenance and training?

Chapter II-4 Net Environmental Benefit Analysis (NEBA)

The optimal spill response technique is defined as the one that minimises the potential adverse effect(s) of a spill on the habitat of the region and its biological resources. Responders also need to be mindful that the subsistence lifestyle in the Arctic is inextricably linked to the ecological condition of the natural resources as well as the traditional cultural practices of Arctic residents and that these issues need to be considered in parallel with the NEBA.

NEBA is a process tool that formalises the evaluation and comparison of the expected response effectiveness versus the potential environmental impacts of the oil spill, as well as the response activities (vessels, aircraft, waste disposal etc.). Knowledge of the biology and ecology of the specific region is key to the application of a NEBA in a meaningful and rigorous manner.

Traditional NEBAs involve the following elements (IPIECA 2000) in the process of collecting information on physical characteristics, ecology and human use of environmental and other resources in the area of interest:

1. Review previous spill case histories and experimental results, which are relevant to the area and to response methods which could possibly be used.
2. On the basis of previous experience, predict the likely environmental outcomes if the proposed response is used, compared to outcomes if the area is left to natural clean-up and recovery processes.
3. Compare and weigh the advantages and disadvantages of possible responses with those of natural attenuation.

The Net Environmental Benefit Analysis (NEBA) process provides a strategy for decision makers to select appropriate response options at a specific spill location based on the analysis of environmental trade-offs that may occur from the use of the various oil spill

countermeasures available. The following discussion is based on material in National Research Council (NRC, 2014) prepared by K. Lee, an internationally-recognised environmental scientist.

From an ecological point of view, a NEBA

provides a protocol for weighing the advantages and disadvantages of various spill responses with regard to flora and fauna and their habitats within the specific area of concern, compared with no response (also referred to as natural attenuation). The process also provides a cross comparison of the net environmental benefits of each possible response option, for example, comparing mechanical recovery with dispersants and/or burning. All oil spill response tools should be considered and should have the potential for use if supported by a positive NEBA result. The final decision on OSR strategies should be based on robust environmental considerations, including consideration of knowledge gaps. Ideally, there should be no one default response option. Responders and decision makers should have the flexibility to choose a particular response strategy based on its NEBA ranking as the spill and environmental conditions dictate at the time, rather than being constrained by prescriptive procedures or legislation.

A generic NEBA framework is outlined in “*Choosing Spill Response Options to Minimize Damage: Net Environmental Benefit Analysis*” (IPIECA 2000). In addition to providing information for the selection of the best clean-up methods, the NEBA process also provides an assessment of the long-term effects on an ecosystem as a whole, guidance on the intensity level and operational end-points for clean-up operations, and estimates of likely recovery rates (IMO, 2013; Potter *et al.*, 2012).

Identifying and Protecting Valued Ecosystem Components

Case studies have conclusively shown that the application of aggressive clean-up operations may delay the rates of habitat recovery by causing additional damage beyond the oil spill itself (Baker, 1995). For example, in the aftermath of the *Exxon Valdez* incident, a proposed operation to excavate and wash boulders to remove surface and subsurface oil was shown not to offer a net environmental benefit as the procedures would have altered the sediment structure and delayed biological recovery (Shigenaka 2014).

In the event of a large oil spill, a single spill response strategy is unlikely to provide opti-

mal protection for all environmental resources as more than one environmental compartment (i.e., water surface, water column, sediments, and shoreline) would potentially be impacted. In fact, a response strategy that provides protection for one environmental resource (e.g., chemical dispersion of oil slicks to protect seabirds) may increase risks to another (e.g., toxicity of dispersed oil in the water column). Dispersed oil could present unacceptable risks to sensitive areas important for fishing (e.g. economic losses through closures and perceived or real risk of tainting) or for breeding of fish populations. In using NEBA decision makers select the optimal response strategy based on the protection of priority environmental resources and the countermeasures, which offer them the greatest protection.

NEBA incorporates prioritisation criteria for the protection of Valued Ecosystem Components (VECs) that could be impacted by oiling, clean-up operations, or residual oil. The analysis also considers seasonal variations of these valued ecosystem components (e.g., breeding grounds, migration routes) and the time frame of the restoration of items which may be impacted.

Using NEBA in the Selection of Oil Spill Countermeasures

Responders have a number of clean-up methods available for operations on-water (physical recovery, dispersant applications, in situ burning, and monitoring natural recovery) and on shorelines (manual collection of oil, low-pressure flushing, shoreline cleaning agents, pressure-washing, bioremediation, surf-washing, etc.). There are clear differences in operational limits for each oil spill response strategy (NRC, 2014). Each response method has certain advantages (e.g., speed, efficiency, simplicity), and disadvantages from operational or environmental perspectives (e.g., soot and residue from in situ burning; the low encounter rates for containment and recovery in many open water situations, high volumes of waste generation, etc.). The usefulness of each clean-up method in any given situation depends on factors such as type of oil spilled, environmental resources and habitats threatened; weather and sea state conditions, and

the availability of logistical and operational support. A NEBA should take all of these factors into account during the selection of the optimal response strategy.

Planning a NEBA Strategy for Ice-Covered Waters

The NEBA process should be an integral part of future contingency plans on the grounds that post-spill decisions are best and most rapidly made in light of reasoned pre-spill analyses, consultations, and agreements by all the appropriate organisations. Use of NEBA in contingency planning offers several advantages: extended time frame for analysis; consideration of spill scenarios covering a wide range of environmental factors (e.g., seasonal changes in species diversity and ice cover); time for identification and collection of scientific data; and maximum stakeholder involvement. NEBA should cover a range of oil spill scenarios from small accidental releases associated with routine operations to the “worst case” in terms of oil volume, sensitive species, and environmental factors (e.g., oil under ice). Consideration must also be given to the logistical constraints to be encountered during Arctic oil spill response operations that would influence the efficacy of current countermeasure strategies.

For application in ice-covered waters, in addition to representation from regulators, environmental resource managers, health authorities, technical specialists in oil spill response technologies, and the scientific community, the NEBA process should include the input of regional representatives. Local traditional knowledge is a crucially important source of information on the spatial and seasonal distribution of regional harvesting activities and the identification of critical populations/stocks of fish, birds and mammals upon which regional communities depend. Conducting a regional NEBA that considers a range of possible scenarios, including human impacts, is a significant undertaking that should be planned and carried out in advance of an incident. During the reactive phase of an actual emergency, time and resources are short and the best that can be achieved, typically, is to validate and confirm the findings

of a comprehensive pre-existing NEBA that comes closest to matching the conditions in the field.

Chapter II-5 The Decision Process

The availability and flow of information from a range of sources that include field surveys, remote sensing and trajectory modelling, control the ability of the spill management team to make decisions. The management team coordinates the acquisition and assessment of information and typically asks the key questions:

- What is the type and volume of the spill?
- Where is it likely to go?
- How is the oil behaving and how will it change?
- What are the resources at risk in the spill path, what is their sensitivity and their vulnerability?
- What are feasible response options?

The goal of the decision process is to reach consensus on key response issues that include:

- Response priorities: which risks have time lines with respect to oil contact
- Operational priorities: the sequence of response activities
- Response and treatment guidelines: what can be done and what cannot be done
- End Points: when to stop (particularly important for shoreline cleanup)
- Completion: the criteria or standards that determine when the response has met the objectives.

In an environment with static ice and snow conditions, the response timelines may be extended if oil is contained, concentrated, and trapped for long periods. In dynamic ice conditions, the decision process must be flexible to quickly recognise and adapt to ever-changing oiling and environmental conditions. The decision process typically involves the assessment of constantly changing information and data to develop and continuously update objectives and strategies.

PART III – Background: Key Planning and Response Elements

Chapter 1: Marine and Coastal Oil Spill Scenarios

Chapter 2: Arctic Coastal and Marine Ice Environments

Chapter 3: Coastal Processes and Shoreline Types in Ice- and Snow-Affected Coastal Regions

Chapter 4: Response Infrastructure and Logistics in Ice- and Snow-Affected Marine and Coastal Arctic Regions

- Oil in ice spill scenarios can be categorised according to the following three main elements that are developed in more detail in the following sections:
 1. Oil type: e.g. diesel, heavy fuel oil, refined products, crude oil
 2. Spill size: using the Tiered approach to categorise spill size and the appropriate levels of resources required to respond
 3. Spill source: e.g. a sudden batch release, such as a subsea pipeline rupture, a chronic low rate leak from a sunken vessel, or a massive high-rate discharge from a well blowout
- Very different planning and response strategies apply for batch versus continuous spills (e.g., vessel grounding versus well blowout).
- The risk of a spill in ice and snow is expected to increase as polar and sub-polar vessel traffic and oil and gas exploration and development gradually increase.
- Recovery times for habitats or species following exposure to spilled oil can be short term or last for decades depending on location, timing (season), climate, oil type, oil volume, and response actions.

Chapter III-1 Marine and Coastal Oil Spill Scenarios

a. Introduction and Background

The Arctic region is currently the major focus of the media, government, and many other organisations worldwide, reflecting the rapid pace of Arctic climate change and concerns about the environmental risks associated with projected new developments (i.e. shipping, oil and gas, mining).

Trans-border issues, covering multiple jurisdictions, can potentially complicate the ability to conduct a unified spill response. Examples where marine borders separate ice covered waters governed by different Arctic nation states include Russia/USA in the Chukchi Sea, Russia/Norway in the Barents Sea, USA/Canada in the Beaufort Sea, Canada/Denmark in Baffin Bay and Davis Strait, and neighbouring states in the Baltic Sea. In general, these regions are characterised by

a good level of cooperation and numerous agreements are in place to ensure sharing of resources and communications to deal with pollution emergencies (Table III-1.1).

In a significant advance towards enhanced cooperation, eight Arctic nations recently signed an overall *Agreement on Cooperation on Marine Oil Pollution Preparedness and Response in the Arctic* (Arctic Council, 2013). The objective of the Agreement is to strengthen cooperation, coordination, and mutual assistance among the Parties on oil pollution preparedness and response in the Arctic in order to protect the marine environment from pollution by oil.

The Agreement acknowledges the role of the International Maritime Organization (IMO), in particular in the development and adoption of additional rules and standards to address risks specific for operations in the Arctic environment. Other key provisions in the agreement include recognising, being conscious of and/or mindful of:

- The threat from marine oil pollution to the vulnerable Arctic marine environment and to the livelihoods of local and indigenous communities,
- The need for prompt and effective action and cooperation among the Parties in order to minimise damage that may result from an incident,
- Recognising the challenges posed by harsh and remote Arctic conditions on oil pollution preparedness and response operations,
- The increase in maritime traffic and other human activities in the Arctic region, including activity of Arctic residents and of people coming to the Arctic,
- The fact that indigenous peoples, local communities, local and regional governments, and individual Arctic residents can provide valuable resources and knowledge regarding the Arctic marine environment in support of oil pollution preparedness and response,

Bilateral and Multilateral Agreements/Arrangements	Signatories
Canada-US Joint Marine Pollution Contingency Plan www.dfo-mpo.gc.ca/Library/343409.pdf	Canada, USA
Convention on the Protection of the Marine Environment of the Baltic Sea Area, 1992 (Helsinki Convention) http://helcom.fi/about-us/convention/	Denmark, Finland, Russia, Sweden (and other non-Arctic signatories)
Agreement Between Denmark, Finland, Iceland, Norway and Sweden about Cooperation concerning Pollution Control of the Sea after Contamination by Oil or other Harmful Substances www.copenhagenagreement.org/ www.ust.is/library/Skrar/COPA/engelsk.pdf	Denmark, Finland, Iceland, Norway, Sweden
Agreement between the Government of the Russian Federation and Government of the Kingdom of Norway concerning Cooperation on the Combatment of Oil Pollution in the Barents Sea, 1994 (no link available)	Norway, Russia
Agreement Between the Government of Canada and the Government of the Kingdom of Denmark for Cooperation Relating to the Marine Environment www.treaty-accord.gc.ca/text-texte.aspx?id=101887	Canada, Denmark
Agreement between the Government of the Union of Soviet Socialist Republics and the Government of the Republic of Finland on Co-operation in Combating Pollution of the Baltic Sea in accidents involving oil and other harmful substances, 1989 www.finlex.fi/fi/sopimukset/sopsteksti/1990/19900054	Finland, Russia
Agreement between the Government of the Union of Soviet Socialist Republics and the Government of the United States of America concerning Cooperation in Combating Pollution in the Bering and Chukchi Seas in emergency situations, 1989 www.dec.state.ak.us/spar/perp/plans/uc/mou/Kp-US_USSR_89.pdf	Russia, USA

Table III-1.1 Existing Bilateral and Multilateral Agreements or Arrangements Governing Pollution Response (Source: Arctic Council 2013).

- The expertise and roles of various stakeholders relating to oil pollution preparedness and response,
 - The Parties' obligation to protect the Arctic marine environment being mindful of the importance of precautionary measures to avoid oil pollution in the first instance,
 - The importance of the Arctic marine ecosystem and of cooperation to promote and encourage the conservation and sustainable use of the marine and coastal environment and its natural resources, and
 - The importance of exchanging information, data and experience in the field of marine oil pollution preparedness and response, especially regarding the Arctic environment, and on the effects of pollution on the environment, and of regularly conducting joint training and exercises, as well as joint research and development.
- Commercial voyages outside of the traditional Arctic summer open water season are still relatively few in number, limited to several regions in Canada and Russia:
 - Icebreaking ore carriers serving the Raglan mine in the Nunavik region of Northern Quebec (Fig. III-1.1);
 - Tankers loading Sakhalin oil at the De Kastri terminal on the Russian mainland;
 - LNG carriers loading at the terminal in Aniva Bay on south Sakhalin Island (ice conditions in the port are relatively mild and of short duration);
 - Shuttle tankers loading at the Varandey offshore terminal in the Pechora Sea connected to the Timan-Pechora oil field on land by a 23 km marine pipeline (duration of ice cover at the terminal is 247 days on average with ice thickness in the range 1.3 to 1.8 m);
 - Shuttle tankers loading at the Prirazomloye offshore oil production facility in the Pechora Sea;
 - Norilsk Nickel's fleet of icebreaking container ships carrying commodities and supplies between Dudinka on the Yenisei River and Murmansk as well as other Russian arctic ports, Europe and Asia: and
 - Winter tanker traffic exporting oil from the Novoportovskoye field from a new terminal scheduled for 2016 completion in Ob Bay, Kara Sea.

Source: <http://www.state.gov/r/pa/prs/ps/2013/05/209406.htm>

In order to evaluate levels of risk (frequency and consequences) it is important to consider the range of possible spill sources from vessels (tankers, fishing vessels, offshore support vessels, research icebreakers, cargo ships, cruise ships, etc.) and Oil and Gas (O&G) installations in both exploration and development phases (marine pipelines, offshore platforms, drilling rigs, coastal facilities, etc.).

Continued summer retreat of sea ice in the Northern Hemisphere may lead to significantly different vessel trading patterns within a matter of a few decades. The effects of climate change are being felt more rapidly in the Arctic than in any other part of the world: for example, coastal erosion, permafrost, duration of the summer open-water season, extent of multi-year ice, and higher summer temperatures. There is a widespread concern that oil spill risks will increase as a result of observed increases in vessel traffic and expected growth in oil and gas exploration.

Current marine activity involving transits through ice is captured in the following highlights. Further discussion and information on this topic is provided in Annex B.

In addition to these mostly repeating, destination-specific year-round voyages, a relatively small number of commercial vessels, tourist icebreakers, and research vessels use the Russian Northern Sea Route (NSR) and the Northwest Passage (NWP) through the Canadian Arctic during the summer season. For example, it was reported that 61 vessels utilized the services of the Russian icebreakers during the 2014 season (approximately 40 made the full passage) and as of late November 2014, only 5 vessels were currently operating in the NSR area (<http://www.arctic-liaison.com>).

There is always a possibility that a marginally ice-capable vessel is trapped in severe ice conditions at any time of year but, for the most part, these summer voyages occur under



Figure III-1.1 *Polar Class 4 icebreaking Canadian ore carrier Umiak, serving mines in northern Quebec and Labrador. This vessel and her sister ship the Nunavik are among the most advanced and capable ice-going commercial cargo vessels currently operating in the Arctic (Source: CNW Group/Fednav Limited).*

conditions of predominantly open water. Most vessels have departed the NWP (Beaufort Sea and High Arctic) before the end of October.

It is important to note that the number of Arctic (North of 66°) commercial voyages through significant ice cover is insignificant in terms of global trade, compared with the more than 30,000 vessels using the Suez and Panama Canals in a single year and also when compared with the high levels of year-round shipping activity in the Baltic Sea with over 2,000 vessels active in the region at any given time. The Baltic Sea stands out as the world's most intensely trafficked marine area involving year-round shipping in a sea ice environment. Refer to further discussion of Baltic vessel activity and spill risk in Annex B.

Even greater numbers of fishing vessels routinely transit ice-covered areas or operate in waters close to ice (Northern Norway, Greenland, and Canadian East Coast). Increasing numbers of oil spill support vessels are involved in offshore exploration and seismic programs in the Arctic, along with research icebreakers from both Arctic and non-Arctic nations. Contingency plans for spills

into ice-covered waters should consider the full range of scenarios from frequent smaller spills of a range of oil types to very infrequent large spills from a variety of sources, both fixed and moving.

Although the number of incidents in a particular region (for example, data generated through the 2009 AMSA study described in Annex B) provide a general guide to relative levels of potential spill risk, it is important to realise that only a small proportion of marine incidents ever result in a release of oil.

Caution is advised in basing future vessel traffic projections on recent history: for example, the recent drop in oil volumes moving westbound out of Russian waters around Norway, and the decline in Arctic expedition cruise passengers over the past four years (2010 to 2014). Political instability and economic factors can rapidly shift the patterns of trade in world oil markets, increasing or decreasing the need for future tanker voyages through the Arctic. Future Arctic cruise ships could become fewer in number, but much larger in terms of displacement and numbers of passengers.

Oil and gas exploration and production activities in ice-covered waters are also highly unpredictable and vary depending on individual company strategic plans, seismic prospects, political challenges, permit approvals, legal injunctions and, most importantly, overall economics.

Ongoing oil and gas exploration and production activities in ice-covered waters span a large part of the circumpolar world. Currently six of the eight countries bordering the polar region are pursuing or considering further exploration for oil and gas resources in the Arctic: Canada, Greenland (Denmark), Iceland, Norway, Russia, and the United States. A number of recent/ongoing exploration and production activities are summarised here. Annex C provides an additional overview of current oil and gas exploration and development activities, with examples of arctic rigs and platforms used in the recent past and at present.

Russia is likely to be the most active area for new exploratory drilling in marine areas affected by ice over the next decade, reflecting the fact that the majority of the Arctic's undiscovered oil lies on the Russian continental shelf.

The following summary covers known oil and gas activities in the Arctic study area covered by this Guide that are current or planned in the near future – a number of these activities link to winter shipping whose purpose is to export the oil (see above):

- Summer only exploration in the US Chukchi Sea – a number of wells were completed in the late 1980s but recent efforts have been stalled by legal injunctions. Further drilling is planned.
- Nearshore year-round oil production in shallow water (12 m or less) from gravel islands in the US Beaufort Sea, e.g. Northstar, Nikaitchuq, Oooguruk. Oil from these fields is transported to shore by buried marine pipeline or causeway.
- Summer exploration of the West Coast of Greenland with recent drilling (2012, 2013) but no commercial discoveries to date.
- Summer seismic surveys off NE Greenland may lead to future drilling on recently awarded lease blocks.
- Summer exploration in the Kara Sea (2014).
- Offshore year-round production in the Pechora Sea at Prirazomloye.
- Offshore year-round loading in the Pechora Sea at Varandey connected to an on land field by pipeline (Fig. III-1.2).
- Offshore year-round oil and gas production off the East Coast of Sakhalin with oil transported to shore via marine pipeline.
- Exploration in the Norwegian Barents Sea – all south of the ice edge to this point.
- Limited oil exploration and production in the SE Baltic Sea with 4 platforms known to be active. It is not known if any of these locations are affected by ice (WWF, 2010).

A basic spill scenario combines three key elements: oil type, spill source and spill size. These key factors, along with the prevailing ice and sea conditions, would control the oil fate and behaviour and the possible response options. The following sections (“b” through “d”) highlight issues related to oil type and spill size and consider marine and terrestrial sources. Annex E provides examples of previous spill incidents involving vessels in ice-covered waters and/or cold regions to illustrate the range of accidents that responders could face in future oil-in-ice spill events.

A wide range of petroleum hydrocarbon fluids, from crude oils to refined products, are transported worldwide within ice-covered waters. In addition to the direct risks associated with these voyages, the presence of large volumes of on-board bunkers on all ice-going vessels (e.g. tankers, ferries, cruise ships, container ships, bulkers) poses a significant additional pollution risk. At present, many vessels still rely on persistent IFO 380 fuel for economic reasons. As in the Antarctic, discussions have considered the feasibility of restricting the use of such heavy fuel oils in the Arctic. There are no such regulations currently in place although pending new rules governing sulphur emissions in North America and Europe are forcing operators to consider alternative fuels as an alternative to stack scrubbing.

Crude oil and petroleum products may represent the dominant cumulative volume of hydrocarbons being moved by sea, however the frequency and potential impacts of future

Figure III-1.2 Tankers loading in ice at the Russian Varandey offshore terminal with support icebreakers in attendance.



spills are likely to be dominated by bunker fuels released during incidents with general cargo vessels. Although the quantities of a spill from a tanker may be much larger, the probability of such a spill occurring is extremely low and is continuously declining after dramatic reductions in the past four decades, largely due to improvements in vessel engineering and operating/management procedures: for example, the number of large oil spills (>700 tonnes) during the 2000s was seven times less than in the 1970s (ITOPF accident database).

Oil and gas activities introduce a different level of risk dominated by the remote likelihood, but potentially serious consequences of a blowout leading to a continuous discharge for an extended time period. The record of Arctic drilling over more than four decades is excellent with no significant spill events caused by loss of well containment. Although advancements in drilling technology and preventive measures continue to reduce the risk of a serious loss of control incident, operators must demonstrate their ability to deal with a worst-case discharge event before being granted authority to drill. Such demonstration might include standing contracts with oil spill removal organizations, routine training and exercises, unannounced exercises, and detailed oil spill response plans.

b. Oil Types

A general description of oil characteristics and their classification is drawn from material available on the International Tanker Owners Pollution Federation (ITOPF) web site (<http://www.itopf.com/> – see Annex A for the complete table).

Crude oils of different origin, and even from the same reservoir at different times of year, vary widely in their physical and chemical properties, whereas many refined products have well-defined properties irrespective of the crude oil from which they are derived. Residual products such as intermediate and heavy fuel oils, which contain varying proportions of non-refined components blended with lighter refined components, also vary considerably in their properties.

The main physical properties which affect the behaviour and the persistence of spilled oil are specific gravity, distillation characteristics, viscosity and pour point. All are dependent on chemical composition (e.g. the amount of asphaltenes, resins and waxes which the oil contains). The toxicity of a particular crude oil is largely a function of its degree of solubility and of the aromatic hydrocarbon content.

Specific gravity or relative density: most oils have a specific gravity below that of freshwater (1.0) and are lighter than seawater, which has a specific gravity of about 1.025.

The difference in specific gravity of the oil, ice, and water plays a key role in determining whether most of the oil would reside at or very near the surface of slush ice (light fuel oils) or be submerged at depth and mixed with the ice beneath the surface (heavy bunkers).

The American Petroleum Institute gravity scale °API is commonly used to describe the specific gravity of crude oils and petroleum products. In addition to determining whether or not the oil would float, the specific gravity can also give a general indication of other properties of the oil. For example, oils with a low specific gravity (high °API) tend to contain a high proportion of volatile components and to be of low viscosity. These include products such as kerosene, Jet fuel, and naphtha, as well as raw condensates produced along with gas in many offshore wells. As a general rule, the lower the specific gravity of the oil, then the shorter the persistence of that oil in the environment.

Distillation characteristics of an oil describe its volatility. As the temperature of an oil is raised, different components reach their boiling point one after another and evaporate: that is, they are distilled. The distillation characteristics are expressed as the proportions of the parent oil which distil within given temperature ranges. Some oils contain bituminous, waxy or asphaltenic residues which do not readily distil, even at high temperatures. These are likely to persist for extended periods in the environment.

Viscosity of an oil refers to its resistance to flow. High viscosity oils do not flow as easily as those with lower viscosity. All oils become more viscous (i.e. flow less readily) as their temperature falls, some more than others depending on their composition. This factor is very important in governing the rate of spreading and the equilibrium slick thickness in cold water commonly experienced in ice-covered areas. Viscosity-dependent clean-up operations such as skimming and pumping generally become more difficult as the spilled oil cools: on the other hand, in-situ burning becomes more effective for thicker oil films. The presence of ice and cold water generally support greater equilibrium thickness from spreading in open water or light ice cover and can sustain original thick films trapped be-

tween floes (any relatively flat piece of ice 20 m or more across) or in leads (passage-way or fracture in the ice navigable by surface vessels) in heavier ice. Response strategies for different oils in ice are discussed in Part VI-2.

Pour point is the temperature below which an oil will not flow. The pour point is a function of the wax and asphaltene content of the oil. As an oil cools, it reaches a temperature, the so-called 'cloud point', at which the wax components begin to form crystalline structures. This process increasingly hinders flow of the oil until it eventually changes from liquid to semi-solid at the pour point. For spills in polar regions, the pour point is critical as it would determine whether a particular oil may gel and become semi-solid on contact with cold water: usually less than 5°C in the summer and as low as -1.8°C in winter.

Oils are categorised as Group I through IV according to their API gravity, a generally accepted classification system, and generally exhibit the following characteristics:

Group I	Non-persistent oils such as gasoline, naphtha and kerosene: tend to evaporate and/or dissipate completely in a few hours and do not normally form emulsions.
Group II & III	Include many crudes and IFO 180 fuel oil: can lose up to 40% volume through evaporation on water but tend to form viscous, stable emulsions that can greatly increase the volume of material that has to be recovered and curtail the use of dispersants (particularly Group III).
Group IV	Include heavy crudes and IFO 380 fuel oil: considered very persistent due their lack of volatile material and very high viscosity that precludes evaporation and dispersion.
Group V	Include oils not covered by Groups I-IV as well as products such as silicone, phosphate ester, polyalkylene glycol (PAG), polyester, and biolubes. The properties of these oils and products vary widely. There is no direct experience in conducting a response operation with Group V oils in ice, and they are considered outside the direct scope of this guide. (U5)

The complete classification guide to oil groups (adapted from ITOPF 2014/15) is included as Annex A.

c. Spill Size: the Tiered Approach to Mobilising Response Resources

The concept of viewing spills through a tiered approach has long been used by the oil industry as a means to ensure that the appropriate response structure is developed to handle different types of incidents. The International Petroleum Industry Environmental Conservation Association (IPIECA) defines the tiered approach as follows:

Tier 1: Operational-type spills that may occur at or near a company's own facilities, as a consequence of its own activities. An individual company would typically provide resources to respond to this type of spill. Commercial ships are required to have a shipboard oil pollution emergency plan (SOPEP) to deal with Tier 1 level spills. Details of plan requirements vary with the nation involved.

Tier 2: A larger spill in the vicinity of a company's facilities where resources from other companies, industries and possibly government response agencies in the area can be mobilised on a mutual aid basis. The company may participate in a local co-operative where each member pools their Tier 1 resources and has access to equipment that may have been jointly purchased by a co-operative, for example the recent Greenland Oil Spill Response (GOSR) formed by the Government in 2012.

Tier 3: A large spill where substantial further resources would be required and support from a national or an international co-operative stockpile (e.g. Oil Spill Response Limited (OSRL)) may be necessary. It is likely that such operations would be subject to government controls and direction through a combined inter-agency/industry command centre.

Although a minor spill can be readily handled on board (vessel or facility), the distinction between Tier 2 and Tier 3 spills may be difficult to quantify, depending on the sensitivity of the location, remoteness of the area, etc. There are a number of different definitions regarding what constitutes a "major" spill that could be rated as either Tier 2 or 3. For example, the US Coast Guard defines all spills over 2,381 barrels (384 m³) "major" whereas other analysts and agencies often use 1,000

barrels (119 m³) as a convenient threshold. In the extreme case (very remote likelihood), a worst-case discharge scenario for an exploratory well blowout could involve initial flow rates of 50,000 bpd or more.

d. Marine Spill scenarios

As noted in the introduction to this section, a spill scenario combines three key elements: oil type, spill source and spill size. Responders also need to know the volume flow rate in the case of a continuous release over days or longer, and whether the release is subsea, at the water surface, or on top of the ice. These considerations are summarised below in Figure III-1.3.

The distinction between batch spills, such as a tanker or general cargo vessel grounding (minutes to hours), and continuous releases, such as an oil well blowout (days, weeks or longer), is critically important as this dictates the necessary response time to contain the spill and to protect the shoreline, and, in many cases, the scale and duration of any subsequent on-water response.

There are many differences between dealing with large spill incidents from vessels and marine oil and gas facilities or rigs in remote areas, including the assignment of liability and access to compensation. For a shipping incident there could be multiple tiers of funds to draw on, according to the circumstances: for example, the International Conventions on Civil Liability for Bunker Oil Pollution Damage, 2001 or on Civil Liability for Oil Pollution Damage, 1992 (CLC). In addition the FUND convention and Supplementary fund protocol are applicable to a number of Arctic states and provide considerable further pools of compensation. In some cases, especially in remote areas far from any infrastructure or established oil spill response organisations (OSROs), the ship owner may not have the capacity to mount a rapid response with the necessary resources and a government agency may have to initiate and/or coordinate a response.

In the case of a spill from a coastal or off-shore oil and gas facility or platform, although the liability may be less clear cut, for example, the rig owner or operator, the eventual respon-

sible party with the resources to mount and sustain a large-scale response is almost certainly going to be an international oil and gas major with sufficient financial resources and response equipment already on or close the site to allow an immediate reaction. The actual responsibility for mounting and managing a response operation would vary depending on the national regime in question. Given the unique challenges of mounting a response in remote locations, the need for national-level resources to establish a basic infrastructure and the potential federalisation of a response are likely regardless of the spill's source (vessels or oil and gas facilities and rigs).

A number of general scenarios are described here, according to their source, to demonstrate some key operational differences between dealing with an accidental spill from offshore drilling platforms, subsea pipelines, vessels, or shore facilities.

Offshore rigs or platforms where the responsible party, typically a large oil major, can quickly organise and sustain a high level of response drawing on substantial marine resources already standing by on site, and supplemented by agreements with Tier 3 organisations such as OSRL to quickly provide access to additional equipment from out of the region. In this scenario, the potential location of any possible spill is known ahead of time, for example, the drill site, as is the timing, during the drilling program and while penetrating oil bearing zones. A worst-case discharge (WCD) scenario could involve a continuous flow at high rates involving tens of thousands of barrels per day. Modern capping stack technologies developed during and since the Macondo well blowout were designed to either shut in the well entirely or create a closed system in which all escaping oil would be captured and flowed via a riser system to a surface vessel for processing and then transport. Such operations could be completed in relatively short periods of time (days to weeks). Future drilling applications for exploration wells in North American Arctic waters are likely to require rapid access to a capping system and deployment systems as a condition of drilling. Water depth is an important consideration in implementing this response measure: deploying and successfully implementing a capping

elines

sed structures

stack operation in shallow water (tens of metres) is challenging and as yet untested. Other measures such as advanced blowout preventers and shear rams (e.g. Chevron Canada's Alternative Well Kill System) are applicable to wells in shallow water and can cut through casing and connectors while sealing the well at the same time. These recent developments are intended to make future Arctic drilling safer and reduce the risk of a long-lasting discharge extending into the ice season. These are promising technologies but have not yet been tested in the Arctic.

Loss of well control at the seabed during offshore exploration drilling from floating drill ships or Mobile Offshore Drilling Units (MODUs) could result in a subsea release leading to oil trapped under moving ice. A well blowout at a nearshore facility in shallow water, such as from production islands off the North Slope of Alaska, would result in a surface oil plume being deposited on top of stable landfast ice in the winter or among moving ice floes at freeze up and during breakup. Future Arctic offshore oil production developments out to 100 m of water could involve the use of massive Gravity Based Structures (GBSs) similar in concept as those found in the North Sea or off the East Coast of Canada (Hibernia) or in shallower locations, bottom-founded steel or concrete caissons such as Prirazomloye in the Pechora Sea and Orlan off Sakhalin Island. Worst-case discharges from these types of installations could involve a surface release onto the surface or among moving pack ice.

Oil release

- Batch release
 - most of the among the
- Batch release
 - Most of the ice in thick
- Continuous
 - Oil on the

Figure III-1.3 Scenario combinations with significant ice cover. Source: DF Dickins 2011.

Future Arctic production concepts in deep water could utilise subsea completions with pipeline tiebacks to a GBS closer to shore. At this stage, there is no consideration given to what new form of spill response would be required to deal with an incident at such a sub-sea production installation. This type of OSR planning for new production concepts in ice will be needed as new lease areas and exploration activities progress into more challenging ice covered areas such as northeast Greenland.

Pipeline scenarios involving a batch release over a short time frame are potentially contained naturally by the ice in winter. As with a spill from an exploration drilling rig or producing well, the responsible party is clearly identified and would have significant resources that can be brought to bear very quickly. In many cases, response in the broken ice shoulder seasons at break-up and freeze-up would be more challenging than in the winter as the ice may still be too thick or concentrated to navigate by boat but too fractured or thin to provide a safe working platform. The exact location of the spill may not be known precisely and depends on the design of the spill detection system and valve spacing. A pipeline spill further offshore under moving pack ice would be much more difficult to deal with as much of the oil could be trapped under the ice as it moves away from the spill location.

Vessel scenarios where the spill usually occurs over a relatively short time period and where there is no way of knowing the location of the spill in advance. Exceptions could involve damaged, grounded, or sunken vessels that leak from a known location at relatively low rates over a long time, sometimes decades.

There is a wide range of possible vessel scenarios that could lead to spills in ice-covered waters including, but not limited to:

- Small (Tier 1) spills, for example from burst pipes or drums on the decks of a ship.
- A major tanker accident along a shipping route as a result of iceberg, bergy bit, growler or multi-year ice impact, grounding, or explosion and fire.
- Spills occurring during the oil loading/unloading process at terminals due to a breaking hose or an open valve, offshore ship to

ship transfers, and transfers at many Arctic communities where the lack of a dock or deep water port necessitates fuel transfers by floating hose to the beach.

- Loss of bunkers from structural break-up, collision, grounding or explosion, for example with bulk carriers, container ships, fish processing vessels and cruise ships.
- Loss of bunkers through chronic leaking after sinking.
- Penetration of fuel or internal slops tanks through collision between offshore supply vessels (OSV) and an offshore structure.
- Loss of tow when demobilising or mobilising floating drilling units and/or barges.

Annex E provides further details and illustrations from a number of case studies that highlight possible vessel scenarios. There is no equivalent Annex focusing on marine oil spill case studies in ice from oil and gas activities for the simple reason that during more than 45 years of exploration and production in Arctic waters there has never been a major oil spill from an offshore rig, platform or facility. In contrast, there have been a number of significant terrestrial incidents involving oil spilled on to snow and frozen ground: examples are described in Chapter III-1e below.

e. Terrestrial sources for potential oiled ice and snow

Arctic communities store oil, diesel, and gasoline supplies for home and business heating, aviation fuel, and industrial needs for mining and oil and gas production. Because there are long periods between resupply due to sea and river ice, significant volumes of fuel may be stored in relatively close proximity to the shoreline. For example, the Red Dog mine in Alaska has a storage capacity of 190,000 bbl (22,656m³) at the Delong Mountain Terminal, and Barrow, on the Beaufort Sea coast, has a tank farm capacity of 130,000 bbl (1550m³).

Oil and gas activities on land or in the coastal zone that have the potential to spill oil onto ice and snow include exploration or production activities and pipelines. In developed production fields at the coast or immediately inland, such as the Alaskan North Slope, gathering lines commonly cross rivers



Figure III-1.4 Spill from a pipeline leak onto tundra near the coast in winter. The oil has been exposed by removal of the uniled surface snow (Source: Alaska Clean Seas).

and streams within a few kilometres of the coast. As noted above, in this scenario spills on to coastal lands or into rivers and streams could potentially range from a short-term batch release (a storage tank or pipe rupture) to a continuous release from a blowout.

- In March 1977, nearly 190 bbl (22.7 m³) of No. 2 diesel spilled from a storage tank in Nome, Alaska, saturated into snow near the source and migrated down slope through the snow on to and under adjacent river ice (Allen 1978) just inland of the coast.
- Similarly, in April 1978, approximately 1,090 bbl (130 m³) of diesel leaked from a storage tank in van Mijenforden, Spitzbergen, over a 26-day period before the leak was discovered. The oil spilled onto a snow surface and migrated a distance of 200 m downslope within the snow towards

the shoreline and on to sea ice (Carstens and Sendstad 1979). Some of the oil flowed through cracks into the fjord water under the ice and was trapped against the shore and distributed along the sediments at the high tide level. The oil became visible on land as oiled snow melted near the toe of the backshore slope and on the ice as water first appeared due to melting. As the snow and ice melted the oil was spread and moved by wind on the ice surface and observed nearly 5 km from the release point.

- In March 2006, approximately 5,054 bbl (804 m³) of crude oil leaked from a pipeline on the North Slope of Alaska into snow on frozen tundra over a 5 days period covering 7.7 hectares (Figure III-1.4). Similarly, an April 2014 pipeline leak sprayed oil on to the surface of the adjacent snow (Figure III-1.5).



Figure III-1.5 Oil sprayed onto a snow surface from a pipeline leak (Source: Anchorage Daily News).

Chapter III-2 Arctic Coastal and Marine Ice Environments

- The distribution and character of ice and snow are determined by regional and local surface air temperature in combination with surface water temperatures and surface ocean currents, rather than by latitude.
- For example, in the northern hemisphere, the north-western coastal waters of North America and Europe are ice free to high latitudes in winter, whereas snow and ice in the coastal zone are common at latitudes much further south. The “Arctic” study area covered by this Guide includes Sakhalin Island with up to five months of severe ice conditions over a range of latitudes as far south as 46°N, close to equidistant between the equator and the North Pole.
- On average, sea ice covers about 25 million square kilometres of the earth, or about 2.5 times the area of Canada, constituting 15% of the world’s ocean area. Most sea ice grows during the winter months and melts during the summer months, but some sea ice remains through all seasons and for consecutive years in certain regions, for example, the Canadian Arctic Islands, the Arctic Basin and fjords along the Northeast Greenland coast.
- Permanently or seasonally frozen ground (permafrost) is common throughout the northern polar regions.
- Tidewater glaciers and ice shelves form shorelines and are sources of icebergs and ice islands. Glaciers reach the coast to calve throughout the Arctic (e.g. Nunavut, Greenland, Novaya Zemlya, Svalbard). Ice shelves occur in Canada and Greenland.
- Along with the parent water salinity, the changing properties and characteristics of an ice sheet from freeze-up to break-up (the so-called “ice cycle”) dictate where the oil would reside in the ice, the extent of oiling and the state of weathering among other factors. This knowledge in turn would largely control the selection of response strategies as well as the marine resources required for access and logistics. Annex D contains a detailed discussion of example ice cycles for a number of different ice environments including: offshore, nearshore, riverine and shoreline.

Satellite images clearly show the differences in seasonal Arctic sea ice coverage affected by air and water temperatures and ocean currents. Late February to early March represents the time when sea ice cover in much of the Arctic generally reaches its maximum extent, whereas mid-September usually coincides with the minimum extent (maximum open water). Figure III-2.1 shows the minimum and maximum sea ice extent during March and September for 2013/14. The minimum limits broke new records for shrinking ice extent in recent years, notably 2007 and 2012. The yellow outline shows the median ice extent observed by satellite sensors from 1979 through 2000.

Since 1978, satellites have monitored sea ice growth and retreat and have detected an overall decline in Arctic sea ice. The rate of decline steepened after the turn of the twenty-first century. In September 2002, the summer minimum ice extent was the lowest it had been since 1979. Although the September 2002 low

was only slightly below previous lows (from the 1990s), it was the beginning of a series of record or near-record lows in the Arctic. The new lows, combined with poor winter-time recoveries from 2004 to 2007, heralded a sharpening in the rate of decline in Arctic sea ice. Since 2002, ice extent at the summer minimum has not returned to anything approaching the long-term average (1979-2000). Though winter ice extent has fluctuated, satellite and in situ observations have shown that there is significantly less multiyear ice and more annual ice. http://earthobservatory.nasa.gov/Features/WorldOfChange/sea_ice.php

In general, the sea ice cover in many areas is retreating further in the summer and thinning in the winter. Earlier onset of melting and later freeze-up is leading to expanded summer open water seasons: a trend particularly evident in the Chukchi Sea and Barents Sea areas as well as along the Northern Sea Route. Over 40% of the old ice has either melted or been transported out of the Arctic Basin in the

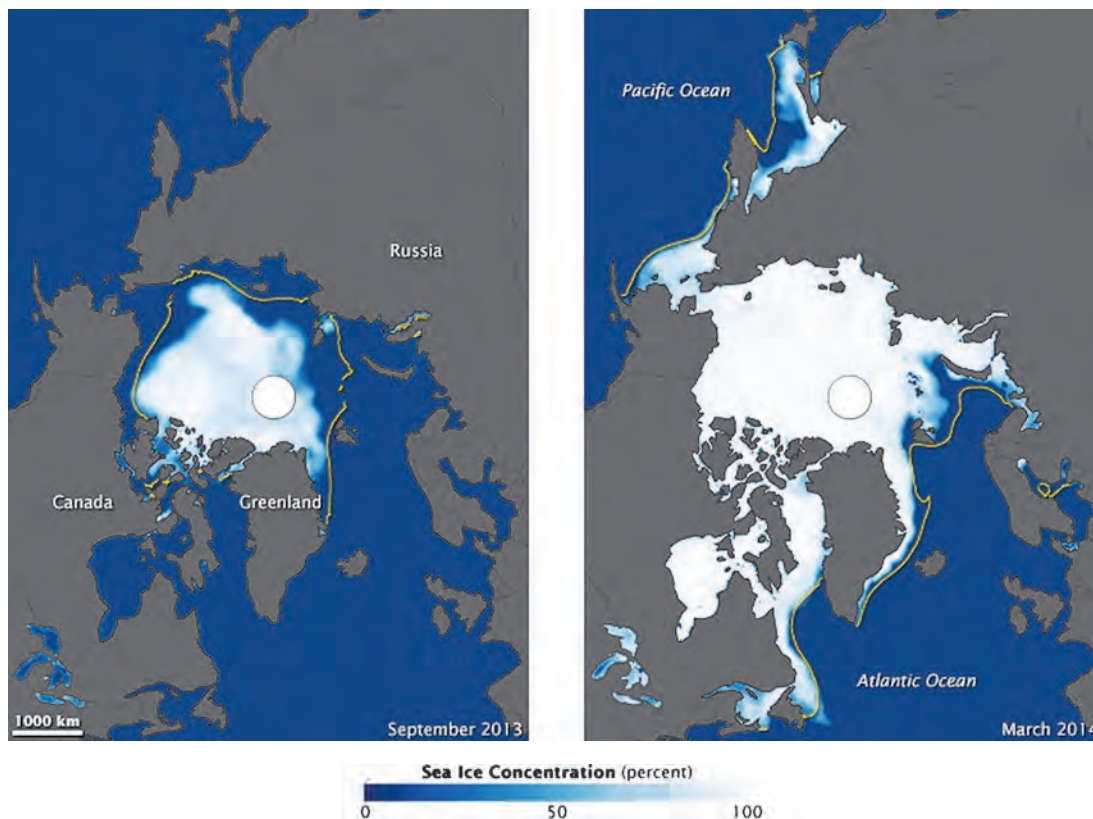


Figure III-2.1 Satellite-derived sea ice extent – March and September for 2013/14 (Source: earthobservatory.nasa.gov).

past 20 years. The result of these large-scale changes in ice composition is reflected in a significant loss of overall ice volume within the Arctic Basin. Ref. <http://www.nasa.gov/topics/earth/features/icesat-20090707r.html>

Projections of the date when the Arctic Ocean typically would have the first sea ice-free summer have been brought forward in recent years. The 2007 IPCC report suggested that this might occur by the end of the 21st century. Since then, the record of actual reductions in sea ice extent have led most scientists to conclude that the first ice-free summer in the Arctic Ocean will be within the next 25 to 40 years, while some claim it could conceivably occur within the next decade². Note that

the term “ice free” in WMO sea ice nomenclature, and as used in producing ice charts, truly means water entirely free of ice. When there is a possibility of trace amounts of ice less than 10% coverage overall, this condition is referred to as “open water”. Climate modellers who discuss “ice free” conditions may use the term in a looser sense and it should be assumed that some ice might still be present in small quantities.

Granskog et al. (2006) summarizes observed long-term changes in the Baltic ice cover related to climate change.

“Jevrejeva et al. (2004) examined the evolution of ice seasons in the Baltic Sea during the 20th century. Their 100-year time series shows a general trend toward reduced ice conditions; the largest change being the length of ice season, which has decreased by 14 to 44 days during the last century. There has also been a reduction of about 8 to 20 days per century to earliest ice break-up which the authors relate to a warming trend in winter air temperatures over Europe. Present climatic models also pre-

² There is a wide range of projections for when the first ice-free Arctic summer will occur. See, for example, Muyin Wang and James E. Overland, ‘A sea ice free summer Arctic within 30 years?’, *Geophysical Research Letters*, Vol. 36, 2009; and Julianne Stroeve, Marika M. Holland, Walt Meier, Ted Scambos and Mark Serreze, ‘Arctic sea ice decline: Faster than forecast’, *Geophysical Research Letters*, Vol. 34, 2007. The most aggressive projections suggest this could occur before 2020 (see, for example, Professor Wieslaw Maslowski, Naval Postgraduate

School, or Professor Peter Wadhams, University of Cambridge).

dict significant large-scale changes also in the Baltic Sea region. These include changes in the water balance of the entire Baltic catchment area, and substantial increase of mean temperatures. The predicted changes are expected to be the most extensive during the cold season. Average winter temperatures in northern Europe may increase by several degrees by the year 2100 (Meier, 2002). Under this scenario, the ice-covered area in the Baltic Sea would decrease by about 45,000 km² for each 1°C increase in the average temperature and during mild winters only the northernmost and easternmost parts of the Gulf of Bothnia and the Gulf of Finland would freeze.”

The significant changes in the area coverage of summer ice as well as the timing of break-up and freeze-up will require frequent reassessments of spill response strategies to cope with the highly variable ice conditions expected in many areas. Although the overall trend may be towards more expansive areas of open water and longer summer ice free periods, flexibility will continue to be the key in dealing with the still highly unpredictable timing of ice retreat and freeze-up.

Record breaking mild ice years can be followed by swings in the other direction the following season. For example, the unusual freezing conditions and gale-force winds during the winter of 2010/2011 resulted in the worst ice cover since 1996, causing about 50 cargo and passenger vessels carrying more than 1,000 people to be trapped by ice in the Northern Baltic Sea for several days before being freed by icebreakers dispatched by the Swedish Maritime Administration. In contrast, the following ice season (winter of 2011/2012) saw a season that, although average in terms of ice extent, was four to six weeks shorter than average in the Bay of Bothnia and two to three weeks shorter in the Sea of Bothnia and Gulf of Finland (Vainio, 2012).

Satellite images of ice conditions on specific dates are used here and in Annex D to illustrate particular ice features and patterns. It must be emphasised that ice conditions are highly variable not only from day to day within a season but also between years. An oil spill response plan should take this variability into account and be prepared for the full range

of conditions experienced at any time during the ice cycle (see section b below).

The first subsections in this Part (“a” through “e”) summarise and illustrate some of the important linkages between global temperature trends, water temperatures and currents, and the formation of sea ice, freshwater lake and river ice, permafrost, ice shelves and iceberg movements in the Northern Hemisphere. Given the breadth of the topic, the coverage here is necessarily brief.

Annex D further discusses the different ice cycles affecting the formation, growth and decay of:

- Offshore Drifting Sea Ice
- Seasonal Shore Zone and Nearshore Ice
- River Ice
- Terrestrial Ice and Snow

a. Introduction to Sea Ice and Basic Terminology

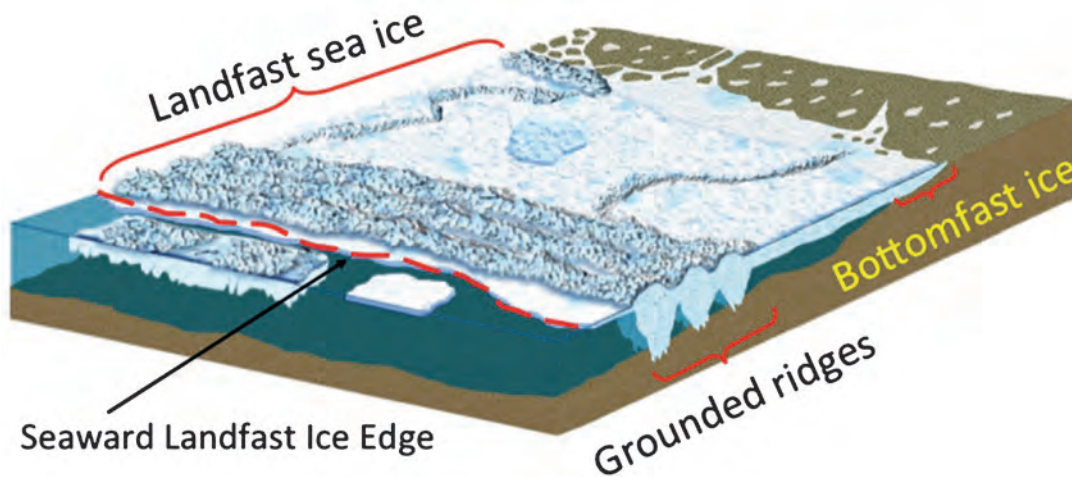
Sea ice in its multitude of forms affects every aspect of spill behaviour, the selection and, most importantly, the implementation of practical and appropriate countermeasures. Sea ice dominates the Arctic marine environment for the majority of the year.

This section introduces the general terms and common processes that govern the ice cycle from freeze-up to melt, and then compares selected regions according to several characteristics important to oil spill response. General descriptions include selected material from the NASA Arctic Theme and National Snow and US Navy NOAA Ice Data Center web pages. Baltic ice properties are discussed separately in Subsection b. following this introduction.

Sea ice has a complicated seasonal evolution that is a function of seasonal temperature variations and mechanical forcing; its structure and evolution differ significantly from the coastal zone to offshore (Figure III-2.2).

Land-fast ice, or simply fast ice, is sea ice that has frozen along coasts (“fastened” to them) and/or in part to the sea floor. Unlike drift ice, fast ice does not move with currents and wind, and tends to be most stable and extensive along shorelines with a broad shallow shelf extending offshore: for example, Alaskan

Figure III-2.2 Cross-section of typical Beaufort Sea ice zones moving from the coast (Source: Used with permission from Geophysical Institute, University of Alaska Fairbanks (Mahoney et al., 2005)).



North Coast, Yamal Peninsula in the Kara Sea, and the Pechora Sea. Out to approximately 2 m of water depth, the ice is grounded for much of the winter (the so-called bottom fast zone) and remains stable and relatively smooth in many areas out to the 10-12 m water depth. This zone is used in many areas to safely construct flooded winter ice roads that can carry heavy equipment including oil spill response gear, for example, off Prudhoe Bay, Alaska. Further offshore, the fast ice often extends out as far as 30 m water depth by mid-winter and remains relatively stable (but not generally safe for surface transport) at these depths in mid-winter, anchored by grounded ridges and rubble.

The distinction between fast ice and pack ice and the location of the ice edge at different times in the winter has important implications for oil fate and behaviour. Ice features embedded in fast ice are generally static, so oil spilled into this stable ice regime is likely to remain very close to the discharge point (within hundreds of metres) for much of the year. In contrast, oil spilled into a pack ice environment beyond the fast ice edge would drift with the ice over time (Dickins, 2011; Wilkinson *et al.*, 2007).

Ice concentration refers to the areal extent of ice relative to open water and is expressed as tenths (/10) of ice coverage (e.g., 1/10 = 10% coverage of ice by area).

Drift ice makes up most of the ice cover in the Northern Hemisphere and consists of ice that floats freely on the surface of the water, as

distinguished from fast ice. Although drift ice can remain static and close to unmoving for weeks at a time, these periods are not predictable and the pack can open or close on short notice (minutes-hours) in response to wind and current driving forces. When packed together in large masses over 6/10 ice concentration, see below, drift ice is called *pack ice*.

Ice movement impacts oil spill response in a number of critical ways:

- controls the film thickness of oil trapped on or under the ice from a continuous surface or subsurface release where the ice sheet is moving past a fixed discharge point;
- dictates how rapidly oiled ice may drift across international borders or impact another country's marine resources e.g. Russia/Norway; Russia/Japan; Canada/Denmark; Canada/USA; and
- affects the magnitude of the offshore logistics plan needed to track, detect and access oil in the ice through the winter and into the following spring.

Drift or pack ice is often in motion, driven by winds acting over long distances. Movement rates can exceed 50 km per day in many areas during storm events and consistently maintain 10 km or more per day over long periods in areas with a strong coastal current, such as off East Greenland. Ice can move great distances over the course of a winter. For example, the

net displacement of ice past a subsea mooring ADCP (Acoustic Doppler Current Profiler) site north of Tuktoyaktuk, Canada, between mid-October and mid-May was almost 2000 km through the winter of 2007-2008 (Melling and Riedel 2004). The east coast of Sakhalin Island represents one of the most dynamic ice pack environments in the world, with average movements of 30-50 km per day.

A diverging, opening, ice field can redistribute the floes into lower concentrations over tens of hours or less: opening large leads and openings that appear as lakes within the pack – polynyas. These exposed open areas rapidly refreeze in the winter in response to the large temperature difference between water and air: over -30°C in many cases. The heat lost in this process can give rise to “frost smoke”, thus limiting visibility.

In contrast, converging or closing pack ice would quickly start buckling, rafting and compressing the weakest ice available: typically the new and young ice that is created from refrozen leads formed in the last diverging cycle. This deformed, ridged and rubble ice, although only making up 10-30% of the ocean area across the Arctic Basin, constitutes half or more of the total ice mass. The rough underside of this ice can effectively contain large oil spills within relatively small areas (see Table IV-1.1).

Ice floes are considered floating ice pieces less than 10 kilometres in their greatest dimension. Larger areas of consolidated ice are generally called ice fields. Moving into the interior of an ice pack from the open sea, floe sizes rapidly increase as the energy of the swell penetrating through the ice diminishes with distance.

Ice which has survived one or more summer seasons of partial melt is called old ice: made up of second year, referring to ice that has survived one full summer, and multi-year ice, two years or older that can circulate for up to a decade within the Arctic Basin or remain static for extended periods in some areas, such as the Canadian Arctic Archipelago. Multi-year ice, which has survived more than one melt season, can be highly variable in thickness, with a typical maximum of 3-4 m when grown as a level sheet, constrained by thermodynamic equilibrium. However, many old ice

floes are much thicker, being remnants of extreme rubble fields or ridges that preferentially survive the summer. These floes can average over 12 metres thick and are clearly identified with a an undulating rough surface and high freeboard, where the ice surface stands a metre or more out of the water, making them clearly visible from the bridge of a vessel or on satellite imagery. The strength and thickness of old ice demands a much higher Polar Class for ice management and response vessels to operate safely and effectively (for example, Figure III-2.3).

Multi-year ice is significantly fresher than first-year ice, without a well-defined network of brine channels (NSIDC; Johnston, 2004). This characteristic has implications for oil migration that are not well understood, although it is generally believed that it may take several seasons for oil trapped under multi-year ice to appear on the surface. Limited field tests with actual oil spilled under multi-year floes (single project) provide inconclusive results (Comfort *et al.*, 1982).

The composition of sea ice in its different growth stages is described in the international Egg Code used universally by most of the world's ice services, including the USA, Canada, Denmark, and Norway. This code breaks the total concentration into the different ice ages that are present: new, young, thin first-year, medium first-year, thick first-year, and old ice made up of second-year and multi-year. The concentration of each age class along with the predominant floes sizes, where known, is shown in the code for polygons of similar conditions drawn on the regional charts distributed daily by many organisations. Supplemented by available airborne reconnaissance and satellite imagery, daily ice charts are the key to understanding the make-up and short-term changes to the ice cover that would affect the choice of practical and appropriate response strategies. Many Arctic nations produce ice charts at frequent intervals, for example: Canadian Ice Service, National Ice Center (USA), Danish Meteorological Institute, Norwegian Meteorological Institute, and the Arctic and Antarctic Research Institute (Russia).

The Canadian Hydraulics Centre and Transport Canada provide an excellent pic-

torial guide to ice regimes in their 2003 publication. A series of exceptional photographs taken from on board icebreakers portray concentrations, stages of development (growth), and stages of decay (melt). https://www.tc.gc.ca/media/documents/marinesafety/tp14044e_aissr_guide.pdf

b. Introduction to Freshwater or Brackish Lake and River Ice

- Fresh and/or low salinity ice form each winter in Arctic and sub-Arctic areas with winter shipping, for example Ob Bay and Yenisei River in Russia, and the Baltic Sea.
- The crystal structure of fresh water river or lake ice is very different than sea ice. The lack or paucity of brine channels could affect the timing and process of oil migration during the spring. Refer to a discussion of the migration process in Chapter IV-1e.

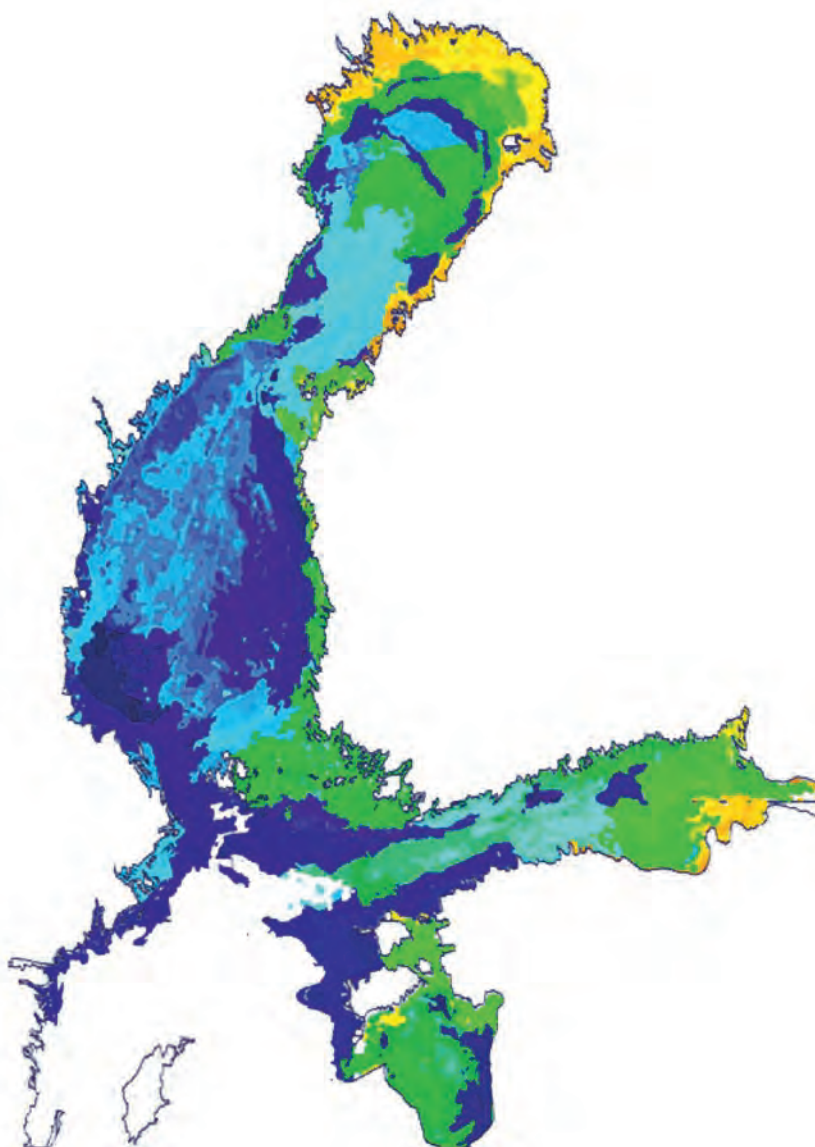
The process by which fresh water ice forms is very different from that of sea ice. Fresh water is unlike most substances because it becomes less dense as it nears the freezing point. Very cold, low-density fresh water stays at the surface of lakes and rivers, quickly forming an ice layer on the top. In contrast to fresh water, the salt in ocean water causes the density of the water to increase as it nears the freezing point, and very cold ocean water tends to sink. As a result, sea ice forms slowly, compared to fresh-water ice, because salt water has to sink away from the cold surface before it cools enough to freeze. A greater accumulation of days below freezing is required to initiate ice in the ocean compared to fresh water. Furthermore, other factors cause the formation of sea ice to be a slower process. The freezing temperature of salt water is lower than fresh water; ocean temperatures must reach -1.8°C to freeze.

The Baltic Sea is the world's largest brackish water basin, has a surface area of about $377,000\text{ km}^2$ (1610 km long by 190 km wide). The mean depth of the Baltic Sea is only 55 m, and in the Gulf of Finland and the Bay of Bothnia less than 40 m (Voipio, 1981). The surface salinity varies from 9 ppt in the south-

ern Baltic Proper to <1 ppt in the innermost parts of the Gulf of Finland and the Bothnian Bay and in proximity of larger rivers. Although ice cover varies from year to year, during an average winter about half of the Baltic Sea's surface is ice covered. As this is a vitally important waterway for transportation and shipping, sea ice can be a major hazard for passenger and commercial vessels during the winter and early spring.

Figure III-2.3 shows an example of the ice thickness present in the Gulf of Bothnia, Gulf of Finland and Gulf of Riga on March 14, 2006. Large areas have open water or only very thin ice and the maximum predicted thickness shown in the example approaches 70 cm in the extreme north. There is considerable annual variability in both the overall area extent of the Baltic ice cover, regional conditions and ice thickness in any given winter. The northern

Figure III-2.3 Ice thickness distribution in the north, south and eastern areas of the Baltic Sea on March 14, 2006 (Source: Finnish Meteorological Institute).



basin of the Gulf of Bothnia, known as the Bay of Bothnia, typically ices over in early January, whereas the Gulf of Finland and the Gulf of Riga usually freeze in late January. Normally, the ice reaches a maximum extent in February or March.

In terms of the extent and importance for winter shipping, the Baltic Sea stands out as the dominant area of brackish ice in this Guide. For this reason it is treated here independently from the summary of the different sea ice environments in Section III-2c. Gronskag *et al.* (2006) provide a review of the state of knowledge of the Baltic Sea ice environment focusing on its crystal structure, differences from, and similarities with, normal sea ice.

“Although the seasonal ice cover of the Baltic Sea has many similarities to its oceanic counterpart in Polar Seas and Oceans, there are many unique characteristics that mainly result from the brackish waters from which the ice is formed, resulting in low bulk salinities and porosities. In addition, due to the milder climate than Polar regions, the annual maximum ice extent is highly variable, and rain and freeze-melt cycles can occur throughout winter. Up to 35% of the sea ice mass can be composed from metamorphic snow, rather than frozen seawater, and in places snow and superimposed ice can make up to 50% of the total ice thickness.

Land-fast ice in the Baltic also greatly alters the mixing characteristics of river waters flowing into coastal waters. River plumes extend under the ice to a much greater distance, and with greater stability than in ice-free conditions. Under-ice plumes not only alter the mixing properties of the waters, but also result in changed ice growth dynamics, and ice biological assemblages, with the underside of the ice being encased, in the extreme case, with a frozen freshwater layer.

There is a pronounced gradient in ice types from more saline ice in the south to freshwater ice in the north. The former is characteristically more porous and supports more ice-associated biology than the latter. Ice conditions also vary considerably in different parts of the Baltic

Sea, with ice persisting for over half a year in the northernmost part of the Baltic Sea, the Bothnian Bay. In the southern Baltic Sea, ice appears only during severe winters.

Bulk salinity is a fundamental and routinely measured sea ice property. The brine trapped into the sea ice lattice is important for several reasons. The volume of the liquid brine, which depends on the bulk salinity and temperature, governs the permeability of the ice cover, and is important for the geophysics, biology and remote sensing of sea ice covers. The thermal conductivity, mechanical, electrical, optical, and acoustical properties are in many cases a function of the sea ice porosity, i.e. brine volume. Many sensors such as ground penetrating radar are highly sensitive to changes in these properties. One can calculate that for ice with a bulk salinity of 1 part per thousand, a temperature as high as -1° C is needed to create brine volumes large enough for Baltic Sea ice to become permeable (that is, if the relation between ice permeability and porosity holds true for the low saline Baltic Sea ice as it does for more saline sea ice). Low brine volumes affect transfer across the ice/water interface, which is important for processes such as nutrient replenishment for ice-associated algae, for convective heat transport through the sea ice, as well as for desalination processes of Baltic Sea ice.”

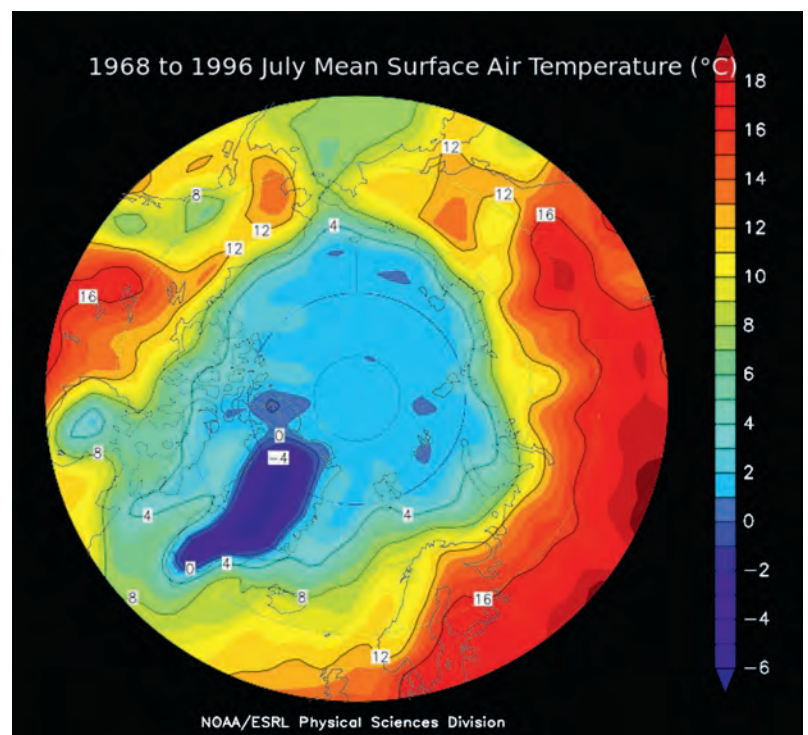
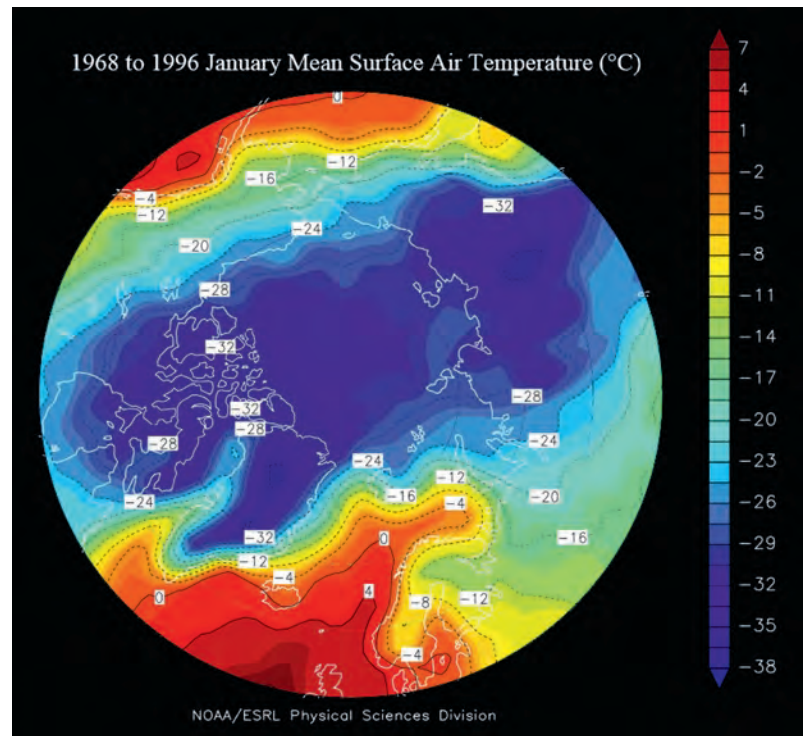
These desalination processes described in Gronskag *et al.* (2006), with references to many other ice researchers, create the pathways necessary for oil trapped within sea ice from a winter spill to rise to the surface as the sheet warms in the spring. This process of oil migration could occur at a very different rate in the case of ice formed in the Baltic from low salinity water. This topic is discussed further in Chapter IV-1e (Oil in Ice Fate and Behaviour) based on observations in Arctic field experiments.

c. Sea Ice and Climate in the Arctic

- The majority of sea ice forms in the Arctic Ocean but in winter extends southerly to mid-latitudes on the eastern coasts of Asia, Greenland, and North America.
- The minimum sea ice cover is typically in September and the maximum in late February/March.
- There exists a wide range of ice conditions from grease and slush during freeze up to thick (up to 2-3 m) multi-year ice types.
- Ice regimes range from dynamic and unstable drifting ice, to isolated ice floes and bergs, and stable landfast ice sheets.

The distribution and character of ice and snow in the Northern Hemisphere are determined by regional and local surface air temperatures in combination with surface water temperatures and surface ocean currents. Figure III-2.4 illustrates the high proportion of the northern hemisphere with below-freezing temperatures in winter. Outside the Arctic Ocean, in December the 0°C mean isotherm includes Iceland, the Baltic Sea, and Atlantic Canada, whereas the mean isotherm in July includes only the coastal environments of the Canadian Arctic Archipelago.

Minimum air temperatures for the coldest month are summarised for different Arctic regions in Table III-2.1. Several of these regions span a vast north-to-south extent and have a significant gradation in climate severity versus latitude: for example, the Chukchi Sea and Greenland. Subpolar areas such as Hudson Bay, northern Sakhalin Island and parts of the Northern Baltic Sea can experience a more severe winter climate than many Arctic areas farther north, such as the Barents Sea, West Coast of Greenland, and the Pechora Sea (Table III-2.1). Latitude is not a good determinant of temperature extremes or the number of freezing days. For example, the eastern coasts of North America and Asia are much colder than the western coasts due to the movement of regional cold air masses eastwards from the centre of the continents. As a result of this effect, seasonal snow and ice in the coastal zone are commonly encountered below 40°N.



Superimposed on air temperature patterns, ocean currents play a significant role in the regional climatic and ice regime character. Warm Gulf Stream waters intrude along the northwest European margin beyond the Arctic Circle throughout the year so that the Norwegian and Barents Seas are largely ice free in winter, even though ice forms in the coastal zone (Øksenvåg *et al.* 2009). In the same manner, the Alaska Current carries warm waters

Figure III-2.4 Northern polar mean surface air temperature in January and July. Note the colour scale differs between the diagrams (Source: NOAA/ESRL).

Table III-2.1 *Regional Comparison of Winter Temperature Extremes.*

Region	Mean Annual Temperature Coldest Month °C
Chukchi Sea	-16 to -27
US and Canadian Beaufort Seas	-27
Canadian Arctic Archipelagos	-34
West Greenland	-12 to -18
East Greenland	-16
Pechora Sea	-17
Barents Sea – Shtokman	-8
South Kara Sea	-25
Sakhalin Northeast Coast	-20
North Caspian Sea	-25
North Baltic Sea (Oulu, Finland)	-10

along the west coast of North America into the Gulf of Alaska so that the oil pipeline terminal of Valdez in Prince William Sound is an ice-free port (Figure III-2.5).

By contrast, the Labrador Current along the northeast coast of North America, the Kamchatka Current and OyaShio Currents on the north-eastern Asian coast carry cold waters south, which accentuates the already cold climate of these regions regardless of their relative southerly location below 40°N. The combination of the southerly East Greenland Current with the easterly flow of cold continental air explains the regional difference between east Greenland and the more mild southwestern Greenland coastal environments. The cold Labrador Current moves ice bergs from the west Greenland glaciers south

as far as into the oil production fields on the Grand Banks and Flemish Cap off Newfoundland (Figure III-2.6). Although some of these areas are outside the boundaries defined as “Arctic” in this document, it is important to understand the underlying climate and ocean dynamics that make specific Arctic regions more or less severe in terms of ice coverage, thickness and persistence.

The overall extent of the ice cover in the Northern Hemisphere changes significantly through the seasons, reaching a minimum at the end of the melt season in September and a maximum typically in February/March – extending into April in some areas such as the Barents Sea (see Figure III-2.1 above).

There is wide diversity in ice forms at different times of year and in different areas in

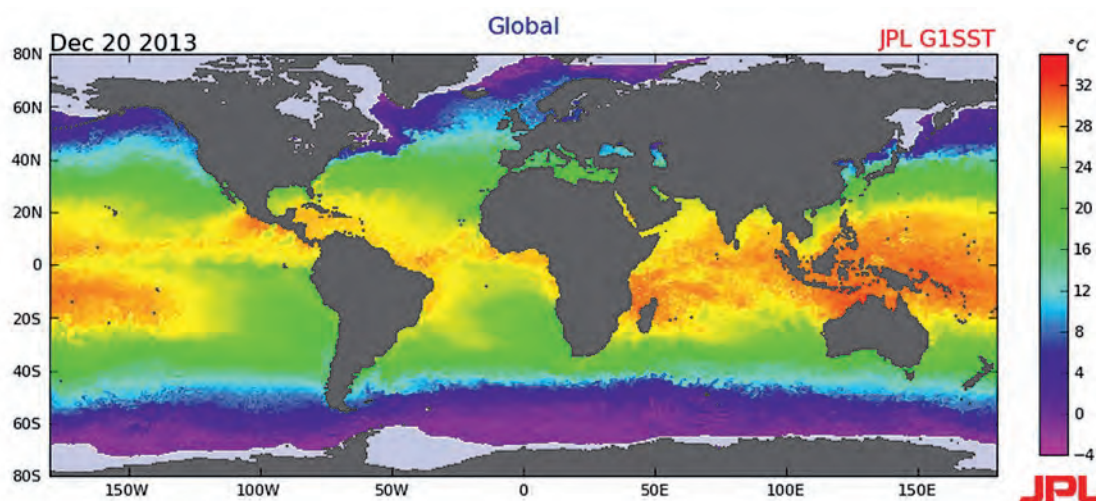


Figure III-2.5 *Sea surface temperature December 13 2013 (Source: JPL).*



Figure III-2.6 Source and drift paths of North Atlantic icebergs (Nazareth and Steensboe, 1998).

the Northern Hemisphere. Photos in Figure III-2.7 show a range of different ice conditions viewed from ships and helicopters in areas as diverse as Northern Norway, Barents Sea, Northwest Passage, and the Beaufort Sea (Dickins, 2012 in Potter *et al.*, 2012).

Figure III-2.8 identifies twelve regions selected to provide a broad cross section of different sea ice regimes.

The following table compares ice conditions between the ten Arctic areas located in Figure III-2.8. Bohai Bay and the North Caspian Sea are not included in the study area covered by this Guide. The Baltic Sea ice environment comprises ice cover formed from very low salinity water and is discussed separately above in Chapter III-2b as well as in Annex D describing the ice cycle.

Figure III-2.7 Examples of the wide variety of sea ice conditions that would determine the spill behaviour and fate and the choice of response strategies. (Photo credits: D. Dickins; except (D) – E. Owens).

- A** Grease ice at freeze-up
- B** Slush and pancake ice
- C** Grey ice with an ice-berg wake
- D** Freeze-up along the coast with an ice foot forming
- E** Mix of grey, grey-white and thin first-year
- F** Thin first-year ice with a young bear
- G** New rubble and ridging in thin first-year ice
- H** Consolidated thick first-year pack ice
- I** Surface of a multi-year (old) floe
- J** Open drift ice 6/10 ice concentration with small to big floes (20 to 2000 metres)

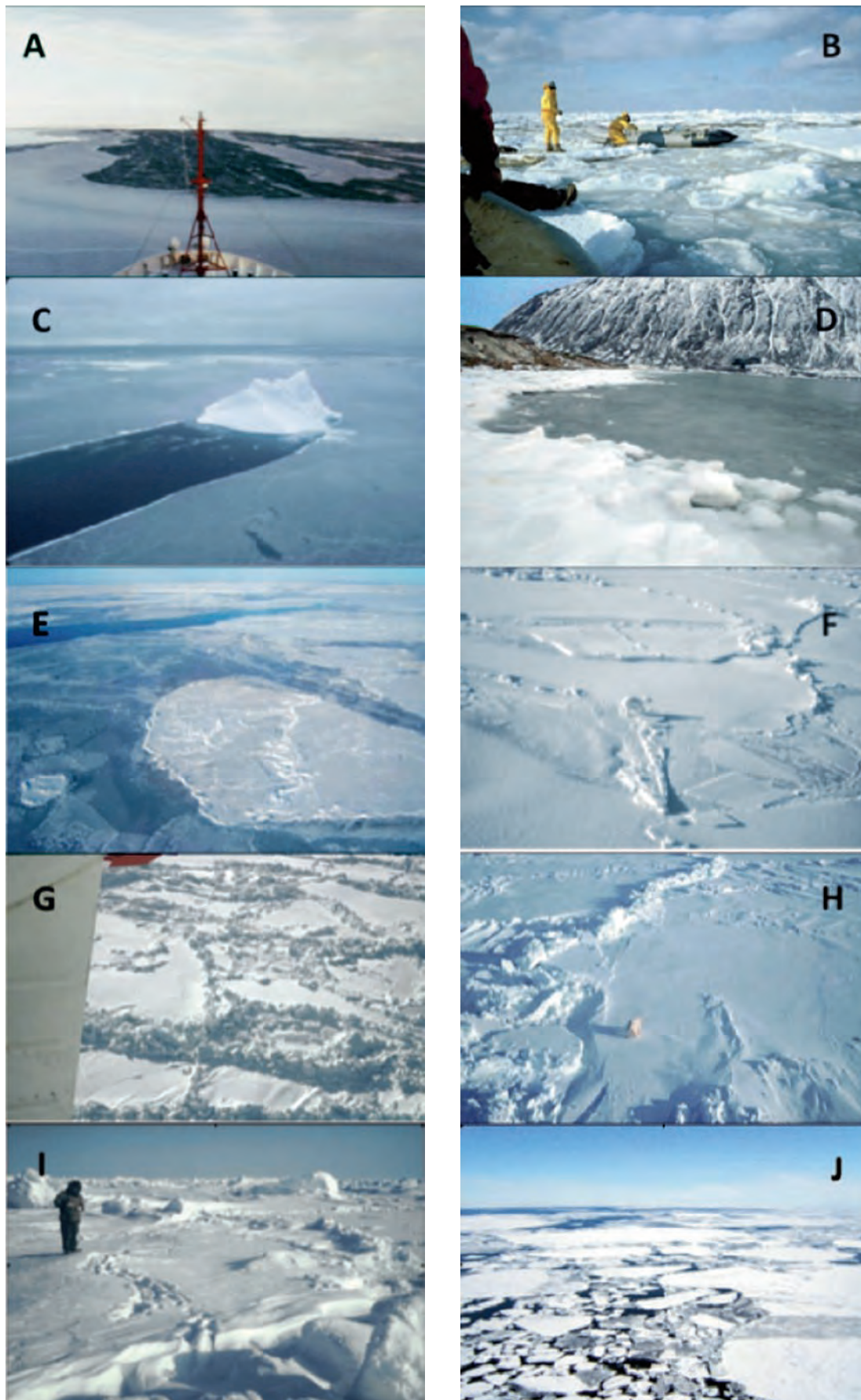
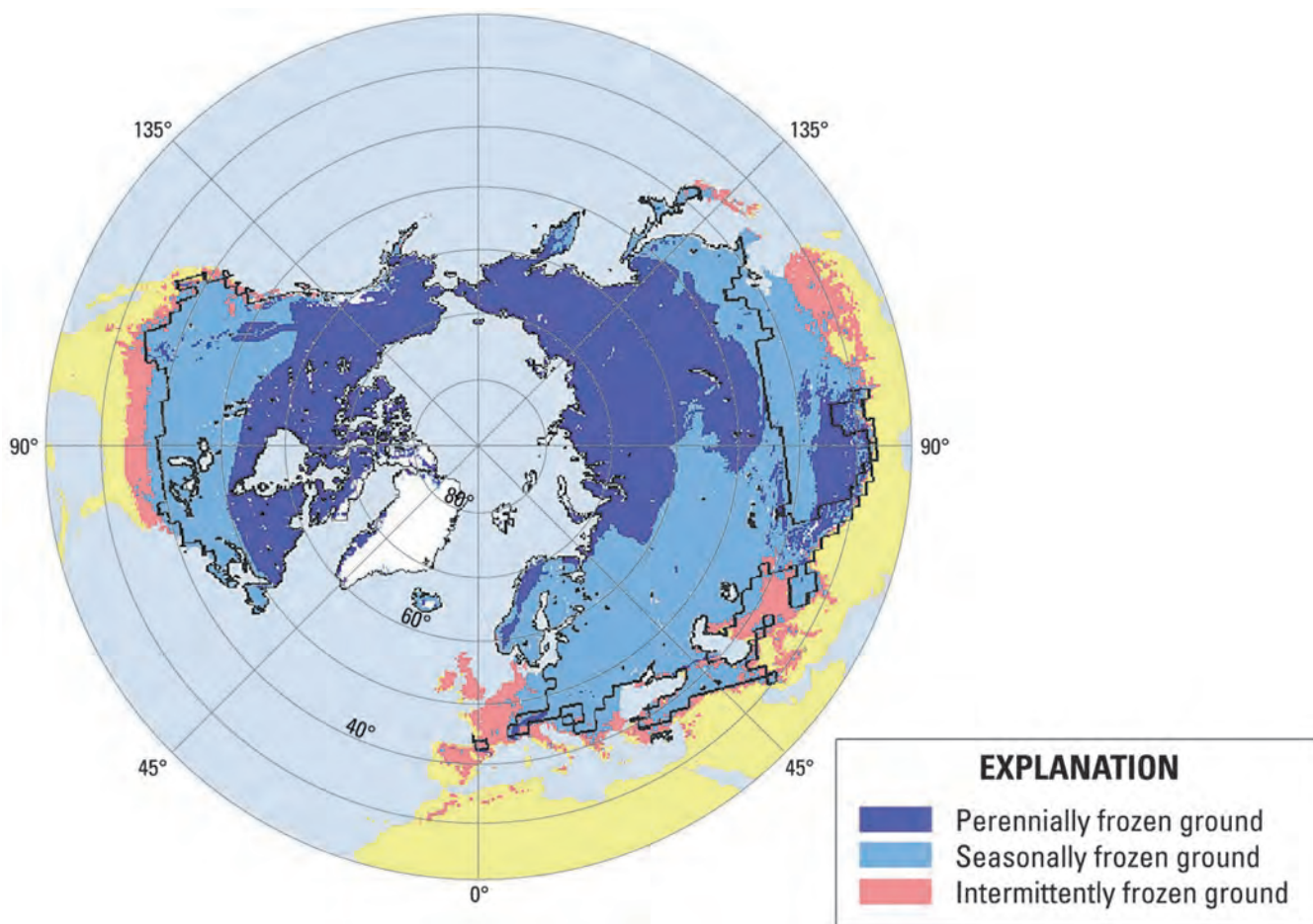




Figure III-2.8 Location map showing Arctic areas used to compare ice conditions.

Overview of Sea Ice in Selected Arctic and Sub-Arctic Areas			
Country	Geographic Region	Key Features of the Marine Environment	Comments
USA	Chukchi Sea	<ul style="list-style-type: none"> Dynamic Occasional multi-year ice Varying severity with latitude Limited fast ice Extensive winter leads Severe short period summer wave climate 	Level thickness varies by close to 1 m from approx. 2 m off Point Barrow to just over 1 m approaching the Bering Strait.
	Beaufort Sea	<ul style="list-style-type: none"> Variable drift (static periods) Frequent leads (variable) Occasional old ice Extensive stable fast ice area Ice conditions tied to water depth and shoals out to 30 m 	Distinct progression of ice regimes moving out from shore. Nearshore ice formation and decay largely controlled by river discharge and barrier islands.
Canada	Beaufort Sea	<ul style="list-style-type: none"> Similar ice severity to US Beaufort Sea except earlier clearing by 1-2 months (May-June) Greater expanse of open water in summer. 	Mackenzie River discharge dominant feature. No Barrier Islands. Lower chance of encountering old ice nearshore than US side.
	Arctic Islands (Sverdrup Basin)	<ul style="list-style-type: none"> Fast ice for 10-11 months Limited summer break-up Predominantly old ice Limited ice movement Average ice thickness 3-5 m 	Periodic cycles of mobility, ice export and replenishment ~10 years.

Overview of Sea Ice in Selected Arctic and Sub-Arctic Areas			
Country	Geographic Region	Key Features of the Marine Environment	Comments
Greenland (Denmark)	East Coast Greenland Sea	<ul style="list-style-type: none"> Highly dynamic Limited fast ice at coast Multi-year ice all year Ice thickness and summer clearing depends on latitude Ice mostly sourced from the Arctic Basin – out of region Moderate winter temperatures 	Northeast coast most severe region in terms of ice speed, duration of ice cover and thickness. Closest analogy is Sakhalin Island with old ice added.
	West Coast Baffin Bay	<ul style="list-style-type: none"> High iceberg densities Highly variable ice season depends on latitude First-year ice generally <1 m thick Open water most of the year in the southwest Predominant polynya or thin ice up to Disko Island Moderate winter temperatures 	Iceberg densities along the coast represent major design challenge. SW coast represents a Marginal Ice Zone (MIZ) transition from ice cover to year-round open water.
Russia	Timan Pechora	<ul style="list-style-type: none"> ~ 6 month significant ice cover Unstable fast ice at the coast Variable pack ice extent Ice nearshore up to 1 m No icebergs or old ice 	Highly variable from year to year – characteristic MIZ.
	Barents Sea NE	<ul style="list-style-type: none"> Icebergs of varying density Pack ice not an annual event (March/April peak extent) Multi-year ice rare to none Significant wave exposure 	Highly variable conditions – MIZ moving rapidly to open water off Novaya Zemlya.
	Kara Sea	<ul style="list-style-type: none"> Varying ice severity north-south Multi-year and Icebergs in north Up to 6 month open water in southwest First year ice from 1.3 to 1.8 m thick Stable fast ice off Yamal (most extensive north of Dikson) 	Similar in overall range of pack ice severity to Chukchi Sea moving south-north.
	Sakhalin NE	<ul style="list-style-type: none"> Highly dynamic (highest ice speeds of all regions) No multi-year ice Predominant polynya through the winter Severe fall storms close to freeze-up Highly deformed pack ice Level ice less than 60 cm average Short term ice motions strongly influenced by tidal currents 	Similar in many respects to northeast Greenland with thicker old ice generated outside the region continually moving down the coast. Limited percentage of locally grown ice.



d. Permafrost, Glaciers and Ice Shelves

Year-round ice in the coastal zone is considered a shoreline type (Chapter III-3b).

Permanently or seasonally frozen ground (permafrost) is common throughout the Arctic (Figure III-2.10). Ice-rich tundra cliffs are formed where permafrost is exposed at the coast. In low-lying areas, the presence of permafrost leads to the development of inundated low-lying tundra shorelines.

Tidewater glaciers and ice shelves form shorelines and are sources of ice bergs and ice islands. The distribution of tidewater glaciers is less associated with the coastal and marine air and sea temperatures, as the source for the ice is a function mainly of precipitation and altitude. Glaciers reach the coast to calve throughout the Arctic (Løsetet *al.* 1999) and in sub-Arctic latitudes in Iceland. Ice shelves form where a glacier or ice cap flow onto the ocean surface as a floating platform. They occur in Canada and Greenland.

e. Weather and Ocean Conditions Affecting Operations

Climate and weather impact many aspects of marine and coastal operations in regions with ice and snow conditions. Adverse weather conditions can severely limit equipment effectiveness, tactical feasibility, especially marine and airborne operations, and can increase risks to the extent that decisions regarding safety become paramount. Table III-2.2 provides examples of risks associated with particular weather and ocean conditions (often called Metocean). The actual operating limits of equipment in an emergency would be determined by the operator for a specific installation and piece of equipment (e.g. model of helicopter).

Many of the risks identified in the table have serious safety consequences and relate also to the discussion in Part VII.

Figure III-2.9 Distribution of northern hemisphere permafrost: C – continuous, D – discontinuous, S – sporadic, I – isolated (Brown et al. 1988).
Source: pubs.usgs.gov/pp/p1386a/gallery5-fig36.html

Sustained wind speeds greater than 25 knots (~13 m/s) could:

- Hinder crane operations on decks of response vessels and equipment with a possibility of swinging, uncontrollable loads;
- Limit in situ burning – a typical wind threshold for successful burn operations is 20 kt (~10 m/s) or less;
- Hamper all marine operations, with the potential for severe sea states, breaking waves and superstructure icing; and
- Hinder helicopter approach and landing on offshore helidecks.

Sea states greater than 1 – 1.5 m in freezing temperatures could:

- Limit boom effectiveness as wave overtopping, leads to loss of contained oil;
- Impede all vessel operations, due to related wind and icing potential from sea spray;
- Contribute to seasickness and/or fatigue, impacting personal safety and effectiveness; and
- Jeopardise safety on deck from slippery and icy surfaces.

Visibility less than visual or instrument flight rule minimums could:

- Limit helicopter landings when cloud ceilings and visibility are below minimums set by government agencies and/or company policy; and
- Limit oil spill monitoring by preventing direct visual observations.

Extreme cold air temperatures less than, for example -35°C, could:

- Impact safety on deck due to dangerous wind chill effects;
- Impact responder safety because of potential for severe frostbite;
- Decrease worker efficiency from fatigue, leading to a need for frequent rest and warm-up breaks;
- Require all equipment (pumps, hoses etc.) to be suitable for use in freezing temperatures. All equipment needs to be fully winterised;
- Contribute to equipment breakdowns due to changes in oil viscosity, hydraulic leaks or brittle failures, and
- Limit helicopter operations – lowest acceptable temperatures are set by the operators and manufacturers.

Table III.2.2 *Examples of risk factors and key weather parameters affecting response operations (from NRC 2014).*

Chapter III-3 Coastal Processes and Shoreline Types in Ice- and Snow-Affected Coastal Regions

a. Shore Processes in Environments with Ice and Snow

b. Shore Features in Environments with Ice and Snow

c. Shore Types and Features in Environments with Ice and Snow

- For the most part, the shore types and coastal processes are the same as in warmer environments, particularly in summer months.
- The exceptions are:
 - in high latitudes where ice is present year-round within the shoreline materials (e.g. as permafrost)
 - where glaciers or ice sheets reach the coast
 - where ice forms seasonally in the shore zone
- Processes:
 - Ice can be present either as a static or dynamic feature
 - Static forms include frozen swash or spray, exposed permafrost, frozen ground, land fast ice
 - edges, glacier or ice sheet cliffs, and snow
 - Ice and snow are dynamic when floes or pressure ridges scour or push sediments, during ice rafting or as a result of blown snow
- Shore types associated with ice and snow include:
 - “year round” boulder barricades, push ridges or scars, ice rich tundra cliffs, inundated low-lying tundra, and ice cliffs at the edges of glaciers or ice sheets
 - seasonal ice layers, frozen ground, stranded floes or pressure ridges, and snow



Figure III-3.1 Winter and summer tundra cliff shoreline (Photo credits: E. Owens).

For the most part, Arctic shoreline types are similar to those of ice-free environments. Our knowledge and understanding of shore zone materials and coastal landforms from warmer coastal environments is applicable to cold climates in most respects, with the addition of ice and snow and the presence of arctic tundra, glaciers, and ice sheets.

Shoreline processes and shoreline materials in environments without ice and snow are the same year round, although, for example, the sand-pebble/cobble ratio may vary on an individual beach due to seasonal wave action. With the presence of seasonal ice and snow the processes and materials can be very different (Figure III-3.1) so that, for example, a permeable substrate such as a cobble-boulder beach can become impermeable by the presence of an ice layer on the beach surface or of frozen waters within the sediments.

The intertidal biological character of shores with ice and snow is strongly affected by short summer seasons, cold air and water temperatures, and ice scour. Life in the shore zone becomes increasingly stressed as the length of winter increases and as temperatures decrease so that plants and animals avoid or have adapted to harsher conditions. This change is evident in salt marshes that show an impoverishment of species with increasing latitude and decreasing temperature (Walter 1977). In high Arctic regions, such as Greenland, the Nunavut Islands, Spitzbergen, and the new Siberian Islands, there may be only one or two associations of grasses, for example, *Puccinellia phryganeodes*, and/or sedges, such as *Carex glareosa*. A second feature of arctic salt marshes is that the typical cross-shore zonation is replaced by an irregular mosaic of communities (Macdonald 1977). Ice rafting can result in the removal

of patches of marsh vegetation (see Figure III-3.4F). In many instances, animals and plants are removed by ice action each winter and attempt to recolonize each spring.

Shore features that are unique to cold climates result from the presence of year-round ice at the coast. These are (a) coastal tundra environments associated with permafrost, and (b) glacier or ice sheets that create ice cliffs at the coast.

Many cold climate coastal environments were glaciated during the last Ice Ages. One legacy of this period is the presence of large volumes of coarse sediment that were eroded and carried to the coastal zone by glaciers and glacial rivers so that the beaches of many glaciated regions are characterised by the presence of pebble, cobble, and boulder sediments (Davies 1972; Forbes and Syvitski 1995).

The roles of ice and snow can affect the response to an oil spill in the coastal zone in a variety of ways as ice and snow can be both an active process and a substrate material that is a feature of the shore zone character.

a. Shore Processes in Environments with Ice and Snow

Shore-zone processes in cold climates where ice or snow may be present year-round or seasonally are the same in most respects to warmer coastal environments. To a large degree, our knowledge and understanding of shore-zone processes in warmer climates is applicable to cold-climate environments with the modifications necessary to account for the role and effects of ice.

The role and relative importance of winds and wind-generated waves is a function of regional and local climate and oceanography

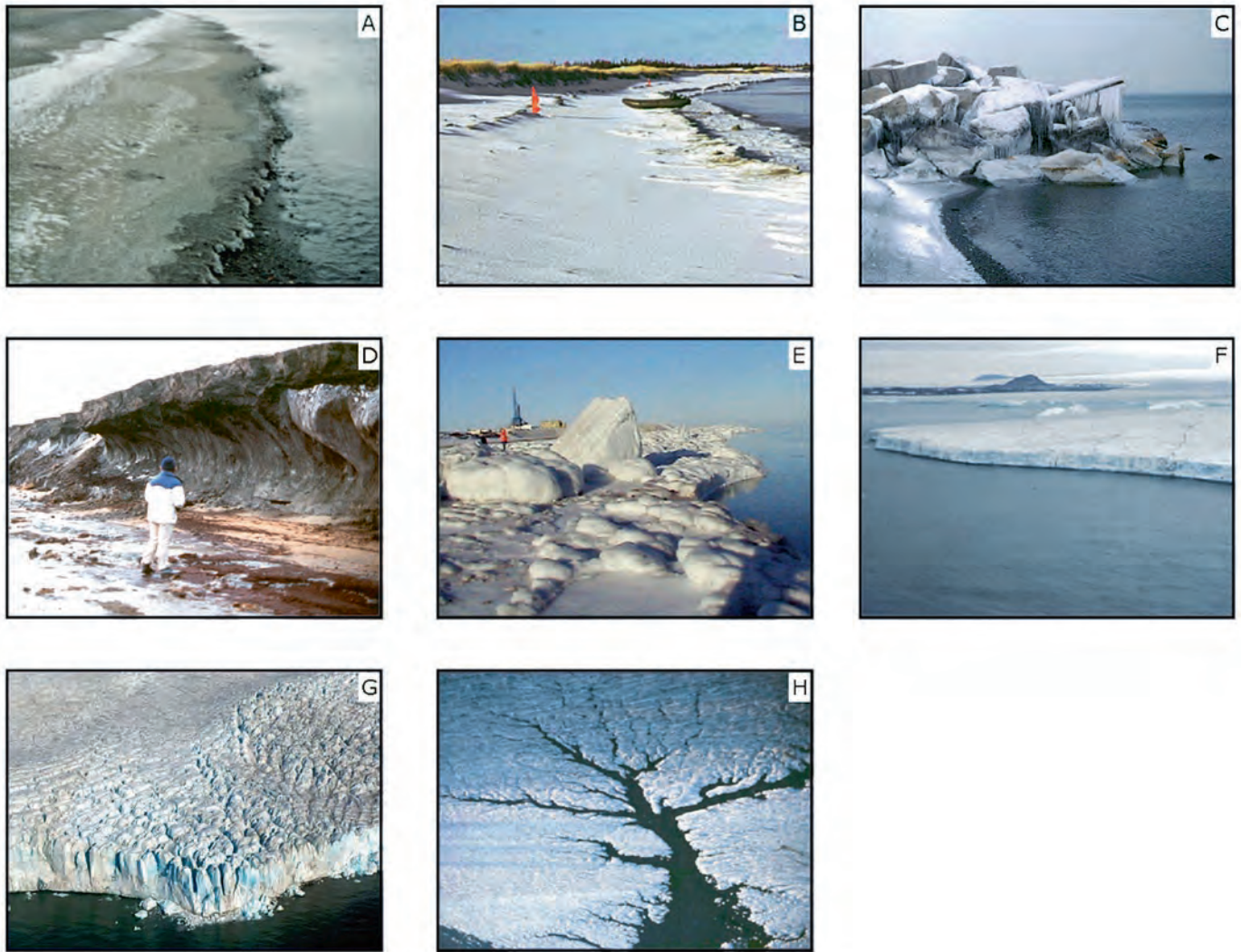


Figure III-3.2 *Static snow and ice forms*
(Photo credits: E. Owens).

- A.** *Frozen swash*
- B.** *Frozen upper intertidal zone (ice foot) and backshore snow*
- C.** *Frozen spray above the intertidal zone*
- D.** *Permafrost exposed in a cliff*
- E.** *Ice edge of land fast ice with frozen in floes*
- F.** *Ice sheet*
- G.** *Calving tidewater glacier*
- H.** *Snow on a marsh*

fetch area and the length of the open-water (ice free) season. The importance of ice in the coastal zone and with respect to shoreline processes and the length of the open-water season at the regional scale are discussed in Chapter III.2 c and d.

Typically, seasonal shore ice begins to form before the nearshore ice and persists after the nearshore ice has broken or melted. The length of the shore-ice season is therefore often longer than the nearshore or offshore ice season typically mapped for marine environments. Regions with seasonal offshore, nearshore, or shore ice are not necessarily low wave-energy environments, but the length of the open-water season may be shortened due to the presence of ice. At one extreme, the presence of snow or ice on a shore may be an occasional event that does not occur each year and the coastal environment is dominated by wave and tidal processes. At the other end of the spectrum, for example, in the Canadian

Arctic Archipelago, shorelines may be ice free for only a few days or weeks each year and during this period open water may be restricted to a narrow coastal belt only a few hundreds of metres wide. Under these conditions, very little energy is available to rework shore-zone sediments or stranded oil. Some ice dominated high-latitude coasts may not become ice-free every year, for example fjords along the Northeast Greenland coast.

Tides are a regional oceanographic process largely unaffected by shore-zone ice. In the many regions with a large tidal range and those macro-tidal environments with a range greater than 6 m (Ungava Bay and Southern Baffin Island; Sea of Okhotsk) tidal water level changes can result in the breakup of shore zone ice into floes (Figure III-3.4B).

Ice is, for the most part, a seasonal element that modifies the shore zone wave, wind and tidal processes but acts as a process itself when:

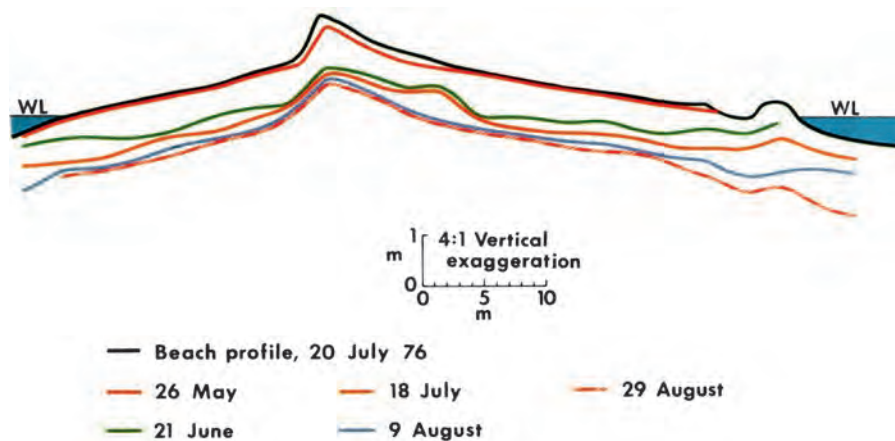


Figure III-3.3 Profiles through a beach that record the lowering of the surface of the impermeable frost table (frozen groundwater) (Owens and Harper 1977).

- ice floes of various sizes that originate from the breakup of sea ice or from calving tide-water glaciers strand at the shore, causing scour and thrusting (Forbes and Taylor 1994), and
- ice that forms at a shoreline is floated or rafted by a rising water level and transports sediment, vegetation or animals that are frozen to the underside of the ice (Lauriol and Gray 1980, Rosen 1979) (Figure II-3.4F).

Ice and Snow Types in Coastal Environments

The range of ice and snow types that can be present in the shore zone and rivers includes both static and dynamic forms.

Static Ice and Snow Forms

- Ice layers of:
 - Frozen swash in the intertidal zone (Figures III-3.2A and D.4A),
 - Frozen spray above the tidal zone (Figure III-3.2C), or
 - Frozen fresh water that has flowed downslope from the backshore;
- Frozen water in a beach or river bank that fills void spaces between sediments (Owens and Harper 1977)(Figure III-3.3);
- Permafrost exposed in cliffs at the shoreline (Figures III-3.2D, III-3.8);
- Ice edges on land-fast ice (Figure III-3.E);
- Ice cliffs of ice shelves and “tidewater” glaciers (Figures III-3.2F, G);
- Loose or compacted snow accumulations (Figures III-3.2B, H).

Figure III-3.4 Examples of dynamic shore zone ice features (Photo credits: E. Owens, except (E) - R.B. Taylor).

- Ice foot and stranded intertidal floes after breakup*
- Ice floes in a macrotidal environment (Bay of Fundy). The ice is brown as this is the colour of the sediment-laden near-shore water*
- Sediment scar formed by ice push*
- Ice push on a lake shore*
- Ice pressure ridge*
- Ice rafted clumps of marsh lifted by tidal ice action leaving water-filled pits in the marsh surface*



Dynamic Ice and Snow Forms

- Individual ice floes:
 - or other small ice forms, such as slush or candle ice, are deposited and stranded on a shore (Figure III-3.4A, B, D),
 - ice sheets or other solid ice forms push into or above the intertidal zone to cause scour or thrusting, and scrape plants on animals on hard substrates (Figure III-3.4C, D),
 - refloated by a rising water level can move or remove sediment, vegetation, or animals frozen to the underside of the ice (“rafting”)(Figure III-3.4F);
- Sheet ice pressure ridges (Figure III-3.4E);
- Wind-blown snow.

b. Shore Features in Environments with Ice and Snow

Shore types associated with processes related to ice and snow or to the presence of ice and snow are either “year round” or “seasonal”.

“Year-round” shoreline types that result from ice-related processes are:

- Boulder barricades formed by ice rafting on intertidal platforms (Figure III-3.5A);
- Sediment ridges created by ice push or ice pressure as ice is grounded on a beach (Figure III-3.4C); and
- ridges and scarred shores on coasts with fine-grained sediments (sands, silts and clays) in low wave-energy environments (Forbes and Taylor 1994).

“Year-round” shoreline types that result from the presence of ice in the substrate are:

- Ice-rich tundra cliffs in which permafrost is exposed at the water line (Figure III-3.2D, III-3.5D);
- Inundated low-lying tundra associated with underlying permafrost (Figure II-3.5C); and
- Ice cliffs of “tidewater” glaciers and ice shelves (Figure III-3.2F, G).

Peat shorelines, although not uniquely polar, are derived from the erosion of coastal tundra coasts.

“Seasonal” ice and snow features that result from a range of static conditions are:

- seasonal ice layers that form as wave splash, spray, or swash freeze;
- water in beach sediments that freezes seasonally and fills the void spaces between sediments;
- frozen fresh water that has flowed down slope from the backshore to the tidal zone; and
- snow accumulations.

“Seasonal” ice and snow features that result from a range of dynamic ice conditions are:

- stranded ice floes created by the breakup or land-fast or offshore ice; and
- wind-blown snow features.

c. Shore Types in Environments with Ice and Snow

This section describes the physical character of the important “year-round” regional shore types that are not present in non-ice or snow environments and summarises oil behaviour for these shore types. Recommended treatment tactics for these shore types are discussed in Chapter II.2e. “Year-round” sediment ridges created by ice push or ice pressure and ridges and scarred shores are not included in this section as these features are in all respects similar to beach sediments in ice-free and snow-free environments.

Ice

The range of ice shore types includes:

- glacial or shelf ice cliffs (Figure III-3.2F, G);
- edges of seasonal land fast ice (Figures III-3.2E);
- surface ice layers (an “ice foot”)(Figures III-3.2B and D.4B);
- beaches in which the interstitial water is frozen (Figure III-3.3);
- permafrost exposed in a cliff at the shoreline (Figures III-3.2D, III-3.5D, III-3.7, III-3.8);
- individual ice floes, granular or slush ice (Figures III-3.4A, B).

<ul style="list-style-type: none"> glacial or shelf ice cliffs edges of seasonal land fast ice 	<ul style="list-style-type: none"> Glaciers that reach the coast create an ice shoreline that can ‘calve’ as ice breaks off the glacier front to form tidewater glaciers. The ice front of a slow moving or retreating glacier may melt without calving. Ice shelves are present on coasts in the Canadian Arctic and Antarctic Oceans where ice sheets extend over the sea and float on the water. Ice shelves range in thickness from a few hundred metres to over 1000 metres.
<ul style="list-style-type: none"> surface ice layers (an “ice foot”) “frozen” beaches 	<ul style="list-style-type: none"> Layers of ice (or an “ice foot”) form seasonally although in high latitude may persist through the open water season. The seaward edge of the ice foot is often a vertical or steep face. Frozen wave splash, spray, or swash can form a coat of ice on an intertidal or backshore surface. Fresh water flowing downslope from the backshore towards the intertidal zone can freeze and may mix with the sea water ice of an ice foot or frozen splash and spray. Ice can form within a beach when water freezes in the interstitial spaces of sediment to effectively create an impermeable substrate.
<ul style="list-style-type: none"> permafrost exposed in a cliff at the shoreline 	<ul style="list-style-type: none"> Erosion of the tundra can expose permafrost at the shore.
<ul style="list-style-type: none"> individual ice floes or sheets of any size ice pressure ridges granular or slush ice 	<ul style="list-style-type: none"> Ice floes or sheets of various sizes can be stranded on a shore. These originate from the breakup of sea/lake ice or from calving tidewater glaciers and ice shelves. Many forms of ice can be driven against the shoreline by wind or current action, including granular or slush ice (Figure III-3.4D). Ridges form where solid ice grounds and buckles under the onshore pressure.

On shorelines with seasonal ice, the ice forms on the surface of the sediment or bedrock in the form of frozen swash or spray or an ice foot (Owens 1976). In these situations, both the surface layer of ice and the underlying geological substrate of the shoreline are considered when planning a response. Ice surfaces do not support significant plant or animal life. Marine mammals may use the edge of the ice to haul themselves out of the water.

Ice is basically impermeable although oil may penetrate where surface cracks are present. Oil behaves differently on the various forms of shoreline ice depending on the character of the surface or texture of the ice, which are linked to the temperature of the air-ice boundary.

The presence of an ice foot or a frozen layer of ice prevents oil from making contact with the shoreline substrate. Oil washed onto the exposed surface of ice, in any of the various forms, is not likely to adhere except when the air temperature is below freezing. During freeze-up, oil on the shore or stranded on the shore-zone ice during a period of freezing temperatures can become covered and encapsulated within the ice. During a thaw cycle or if the surface of the ice is melting

and wet, oil is unlikely to adhere to the ice surface and remains on the water surface or in shore leads.

Oil may be splashed over the ice edge or stranded above the limit of normal wave action. The stranded oil can then be incorporated into the shore-fast ice if temperatures fall below freezing again.

If oil becomes stranded on the substrate in between ice floes and on the floes themselves, its behaviour would be influenced by a combination of ice and that substrate material. Ice in beach sediments, either frozen interstitial or groundwater, can prevent the penetration of stranded oil. Oil behaviour and the selection of treatment strategies also take into account whether the underlying sediments are frozen or not frozen.

Boulder Barricades

Boulder barricades result from the grounding of boulder-laden ice rafts to form elongate rows that typically parallel the shoreline in the lower tidal zone (Figure III-3.5A). Boulders are, by definition, greater than 256 mm in diameter, a little larger in size than a basketball (240 mm), and are only moved by extreme

wave action or ice. Barricades are common on low-lying sheltered coasts with intertidal flats where ice forms in the intertidal zone and that have a distinct slope break in the lower intertidal and nearshore zone.

The formation of a boulder barricade involves several sequential steps and requires specific environmental conditions.

- Boulders freeze within intertidal ice as ice freezes downwards.
- With successive high tides they are lifted and migrate up through the ice as surface ice melts. This process occurs more frequently in the upper intertidal zone (Rosen 1979). In regions with a low tidal range, such as the Baltic Sea, this encasement and freeze-down process results from wind rather than astronomical tides (Tanner 1939).
- The result of this process is that, through time, the boulders appear on the ice surface (Figure II-3.5B).
- When tidal action breaks up the intertidal and nearshore ice before the offshore ice is removed, the resulting shore leads act as corridors for movement of the boulder-strewn ice floes.

- Where the intertidal and nearshore zones are flat then the stranded oil floes ground randomly to create boulder flats. Where a distinct slope break is present in the lower intertidal zone or nearshore zone there is a high probability that ice floes ground there as the ice thickness is comparable to the tidal range.
- Over successive seasons this initial line of boulders traps ice rafts during breakup and perpetuate the process.

Boulder barricades are a stable shore feature and the boulders provide different types of wave exposures and habitats for biological growth. The outer surfaces provide habitat similar to that on bedrock, whereas the large spaces between boulders are more sheltered, shaded, and damp, providing more favourable habitat. Productivity and sensitivity of biological growth can be relatively high; however, as these features result from ice processes the surfaces of boulders are abraded by ice action in winter. Similar to bedrock, sensitivity for large boulders varies in the different intertidal zones.

Boulder barricades are highly permeable. The substrate upon which barricades form



Figure III-3.5 Ice shore types (Photo credits: E. Owens, except (B) – P. Rosen).

- A.** Boulder barricade formed by ice rafting
- B.** Boulder (>1m diameter) on surface of ice flow
- C.** Inundated low-lying high-rim arctic tundra polygons (permafrost)
- D.** Permafrost exposed in eroding tundra cliff



Figure III-3.6 *Oiled boulders.*

may be a mud or sand tidal flat and sands or pebbles/cobbles can be present in the lower portions of the barricade.

Oil stranded on the upper exposed surfaces of the boulders behaves similarly to oil on bedrock. Oil has easy access through the large spaces between the individual boulders, thus coating the inner protected faces of the boulder surface and penetrating into underlying coarse sediments (pebbles/cobbles) if these are present. An oil-covered boulder beach is shown in Figure III-3.6. Oil residence time or persistence is primarily a function of the type of oil and wave-energy levels. Persistence of oil varies greatly between exposed boulder surfaces and protected crevice and subsurface locations. Light or non-sticky oils may be easily flushed out of a barricade by tidal pumping whereas other oil types may leach out slowly over time.

Inundated low-lying tundra

Tundra shorelines and exposed permafrost in the coastal zone create a set of shore types that are unique to North America and Russia. Arctic tundra has a continuous plant cover composed of dwarf shrubs, grasses, mosses and lichens that is underlain by permafrost or seasonal ground ice. Low lying coastal tundra may be flooded or inundated by marine wa-

ters during spring high tides or wind-induced surges (meteorological tides). The landward limits of past surge events usually are marked by log or debris lines. This type of shoreline is dominated by vegetation, although it is not strictly a marine wetland as the plants are not salt-tolerant.

The surface topography of tundra may be characterised by ice-wedge polygons that form as water freezes in contraction frost cracks. This patterned ground is often water-logged in summer months as melt water is contained by the high polygon rims or where wave action breaches polygons or floods low-lying tundra (Figure III-3.5C). These low-lying inundated tundra areas often have a complex and convoluted shoreline and predominantly are a combination of vegetated flats, peat mats, brackish lagoons, and small streams (Hill and Solomon 1999). In areas of higher relief in the shore zone, the subsurface permafrost may be exposed where the easily erodible tundra vegetation is removed by wave action (see Ice-rich Tundra Cliffs below).

The complicated character of the shoreline and the presence of many water-saturated sections may make it difficult to access and move on the land. These shorelines are sensitive to trampling and vehicle traffic during the open-water season and are important bird habitats during the arctic summer.

Tundra has a vegetated soil or peat surface that resists penetration by heavy oil. Heavy oils can persist, however, when buried by sediments or peat deposits. Light oil and light refined products can penetrate the soil, especially when the soil is dry. Residence times for oil on untreated tundra may increase as both the viscosity of the oil and the water content of the tundra decrease. Oil stranded above the intertidal zone weathers only slowly in this terrestrial environment. Complete removal of the oil by natural processes may be delayed until a storm surge or flood event.

Ice-rich tundra cliffs

Tundra cliffs are an erosional feature unique to arctic coasts. They are composed of a tundra (vegetation) mat that overlies peat and exposed ground ice with varying combinations of mixed sediment layers (Figures III-3.2D, II-13.5D).

Ice-rich tundra cliffs are distinct and different from cliffs formed by eroding unconsolidated sediment (ice-poor cliffs), which are predominantly exposed sediment (Figure III-13.1, right). Ice-poor tundra cliffs are unconsolidated sediment cliffs with an overlying surface layer of tundra vegetation and peat. The cliff may have exposed ice only in the upper sections above the intertidal zone (Figures III-3.5D and III-3.8) or have minor

amounts of interstitial ice in the cliff face, typically associated with surface ice wedges (Figure III.3.7) in areas with polygonal patterned ground (Figure III-3.5C).

As the cliff face retreats due to wave action or as thermal erosion melts the ground ice, the tundra and peat materials fall to the base of the cliff. Initially this material falls as fragmented and irregular blocks until it is reworked by wave action. Erosion rates vary considerably depending on exposure to waves during the open-water season and the height of the cliff. Erosion rates may be in the order of 1 to 5 (Solomon 2005) although retrogressive thaw flow slumps (Figure III-3.8) and storm events can result in more rapid local erosion rates in the order of several metres over a few days (Rampton and Bouchard 1975; Lantuit and Pollard 2008). Cliffs range in height from less than 1 m to as much as 5 or 10 m in some cases.

The cliff face is usually either exposed ground ice (permafrost) or deposits of slumped peat and tundra. Despite rapid erosion rates, relatively little beach-forming material are supplied to the intertidal zone as relatively little sediment is present in the tundra soils. The products of erosion are predominantly fines (silt and mud) or peat so that beaches usually are either narrow or absent. Eroded peat commonly accumulates at the base of a tundra cliff or may be transported alongshore (see below). As tundra cliffs are often undercut and are naturally unstable, safety is a primary concern during operations on these shorelines. Beaches are not common in the intertidal zone of this shore type.

The overlying tundra vegetation is composed of living plants and is sensitive to trampling and disturbance. Exposed ground ice surfaces do not support plant life.

Oil washed up onto exposed ground ice is unlikely to stick and will flow down the face of the ice unless air temperatures are below freezing. If the peat is in the form of fragmented or slumped blocks, oil may pool in the spaces within and between the blocks. This is likely to occur at the top of a beach where both oil and peat blocks tend to accumulate. Oil may be splashed over a low cliff onto the tundra surface where it can persist beyond the reach of wave or water action. Sediment



Figure III-3.7 Ice wedge exposed in a coastal tundra cliff (Source: C.F.M. Lewis).



Figure III-3.8 Retrogressive thaw flow slump, Herschel Island, Canada. Photo taken shortly after the event as the permafrost has not been covered by slumps or washing of tundra material onto the exposed back-shore cliff face (Photo credit: E. Owens).

is often deposited on the tundra, sometimes as “perched beaches”, on exposed coasts during periods of storm wave action or wind surges. Oil would usually not persist for long due to natural erosion. Oil on the cliff or the slumped tundra blocks, which also erode rapidly, would be reworked and remobilised by wave action.

Peat shorelines

Peat shorelines are not unique to arctic coasts but are common due to their association with the erosion of coastal tundra. Peat is a spongy, compressible, fibrous material that forms from the incomplete decomposition of plant materials. The peat deposits that are relatively dry are soft and spongy, but peat can behave like a semi-solid or liquid due to its high water content (80 to 90% by weight). Peat has very poor weight-bearing capacity due to its low cohesion. The quantity of inorganic material in peat is often either very low or completely absent. Peat mats are either wet or dry (“dewatered”), erode easily, and are redistributed by wave or current action. Peat slurry, which may look like “coffee grounds”, occurs in the water, often at the edge of the beach or shore. It consists of thick mats of suspended peat that are more than 0.5 m thick and 5 to 10 m wide.

Peat deposits can rest on other substrates, such as a sand beach or low-lying tundra.

Although not typically an important biological habitat, peat shorelines are potential bird-feeding areas.

Heavy oils do not penetrate far into a peat mat, even if the mat is dry or dewatered, but may be buried or become mixed with peat where it is reworked by wave action. Volatile and light oils penetrate into peat more easily than heavier oils. If oil penetrates into the peat mat, relatively little recoverable oil may remain on the surface. Dry peat can hold large amounts of oil, i.e., 1 to 5 kg of oil/per kg of dry peat. Oils that make contact with peat slurry are likely to be mixed and remain so, especially in the low wave-energy areas where these slurries typically accumulate. The slurry has a similar effect to that of a loose granular sorbent and partially contains the oil and prevents it from spreading.

Snow

A snow-covered shoreline can be any shoreline type with seasonal snow that is layered on top of the sediment or bedrock of the intertidal zone. The character of the snow surface can be highly variable, ranging from:

- fresh powder with a soft surface, or drifting snow;
- a loose granular surface that results when powder or packed powder thaws then re-freezes and re-crystallises, or from an accumulation of sleet;
- a hard, dry, crusty surface; or
- wet slush.

As snow accumulates in depth over time, it is common to find a vertical variation in density and porosity. Typically, this steady accumulation is interrupted by the effects of freeze-thaw cycles and wind. As the air temperature oscillates around the freezing point, layers of ice are generated as snow melts during warm daylight temperatures and freezes at night when temperatures drop below zero. If this freeze-thaw cycle is accompanied by precipitation, a range of features can form that may include alternate layers of snow and ice.

Wind action can strip the loose crystals on the surface to expose denser layers of snow below. Blown, powdery snow accumulates in hollows, depressions, or wind shadows. The snow layer itself is not considered to be a sensitive environment. When selecting oil removal tactics, the nature and sensitivity of the underlying sediment, vegetated or bedrock substrates must be considered. **Oil**

The behaviour of oil on a snow-covered surface depends on:

- Type of snow (fresh, compacted, or containing ice layers);
- Air temperature; and
- Surface character (flat or sloping).

If a spill is on the surface of the snow, oil that is above its pour point migrates vertically and horizontally. Oil migrates horizontally from a spill at the base of the snow cover. Oil that is below its pour point could penetrate minimally and run off laterally across the snow's surface. Oil usually penetrates rapidly into the snow column but may be hindered by layers of ice in the snow column that have formed as a result of the freeze-thaw process. As light oil can migrate laterally tens or hundreds of metres within snow, it may be difficult to detect. Dogs have been used to successfully locate subsurface oil in snow.

Snow is an effective natural oil sorbent. The oil content may be very low (less than 1%) in the case of light oils or if the oil has spread over a wide area. The proportion of oil to snow depends on the type of oil and the character of the snow. Snow absorbs more medium crude oils than light products. For example, one cubic metre (m³) of snow can absorb up to 200 L of light oil and as much as 400 L of medium oil. Oil content is lowest on firm, compacted snow surfaces in below-freezing temperatures and highest for fresh snow conditions.

Oil causes snow to melt. Crude oils cause more melting but spread less than gasoline, which spreads faster in snow and over a larger area. Light oils, such as diesel, can move upslope in snow through capillary action as they spread. Fresh snow blowing over oil tends to stick to the oil and migrate down into it, which increases the amount of material to be recovered.

The spreading and weathering of snow is described in greater detail in Chapter IV-2.

Chapter III-4 Response Infrastructure and Logistics in Ice- and Snow-affected Marine and Coastal Arctic regions

- Response strategies in the Arctic are often constrained by remoteness, which is characterised by sparse local populations and infrastructure, few ports and long supply lines.
- In contrast, areas such as North Hokkaido-Sea of Okhotsk, and the Baltic Sea are characterised by denser coastal populations with higher levels of infrastructure and logistics capacity (airports, roads, ports, etc.) to support a large-scale spill response.
- An initial remote area response to an accidental arctic spill may need to rely primarily on airborne strategies and support. It could take many days for additional response vessels to access many areas even in summer. In winter, there are a very small number of high polar class icebreakers (outside of Russia) that could reach a remote spill site and many of these ships are not available on short notice.

Many parts of the northern hemisphere at high latitudes are geographically isolated with vast distances between supply centres. This introduces significant operational challenges in developing a significant level of oil spill preparedness, entailing substantial costs, and amplifying the potential consequences of risk events. Much of the Arctic is characterised by sparsely situated small communities or no population centres at all over vast areas, lack of surface transport, and widely spaced airports, often lacking instrument landing guidance systems or sufficient runway length to support large jet freight aircraft. Perhaps the greatest deficiency in infrastructure in these areas affecting every aspect of a marine or coastal response is the lack of ports capable of handling resupply vessels; this is particularly acute in the North American Arctic with no US Arctic ports north of the Bering Strait and no deep draft port in the Canadian Western Arctic.

A recent report by the National Research Council (2014) discusses the impacts of sparse infrastructure and remoteness on Arctic spill response. These impacts should encourage the selection of response strategies that place minimal demands on the sparse local infrastructure and long lines of resupply. The constraints imposed by remoteness favour countermeasures that can be mounted rapidly over long distances, relying on air support, for example, aerial ignition, and dispersants, as opposed to over reliance on mechanical recovery.

In remote polar regions, response resources are likely to be far removed from the spill location. It may take days for authorities to even reach the site of a vessel incident, let alone begin the task of mounting an effective spill response. For example, in 2010 the MV *Clipper Adventurer* cruise ship ran aground in the Canadian Arctic on a rock initially claimed to be “uncharted”. The Canadian Coast Guard vessel took two days to reach the site (Lloyds 2012). Salvage resources in many remote areas are sparse to non-existent and lightering operations to reduce the risk of further environmental damage could suffer long delays. Although there are known navigation choke points with relatively greater traffic or enhanced ice risk (e.g. Bering Strait, Kara Gate), it is not realistic to pre-stage sufficient

equipment in remote polar areas to cover all eventualities. In contrast, sub-Arctic areas with higher levels of winter traffic, such as the Baltic Sea and Sea of Okhotsk, are generally characterised by a better-developed infrastructure, (airports, roads, ports) and established oil spill response organisations with substantial resources that can be brought quickly to bear on a spill.

The selection of response strategies must include consideration of fisheries impacts, sensitive environmental areas and other local concerns, as well as paying particular attention to national regulations related to controlled burning or dispersant use. Differences in these regulations for the different Arctic nations are reviewed and summarised for both response options in two new reports issued by the Arctic Response Technology JIP 2013/14³.

Remoteness does not preclude response, but can present considerable logistical challenges. For example, the 2014 ExxonMobil/Rosneft drilling programme in the Kara Sea depended on supply and crew change logistics support from Murmansk, approximately 1,500 km distant. The response to the T/V *Exxon Valdez* oil spill represents an extreme example of how a major spill in a remote area could require a massive logistics build-up in a short space of time. After the initial phase of the response in Prince William Sound, Alaska, the entire operation was water based. The marine operations at the peak involved 11,000 total personnel of whom about 3,400 worked on shoreline treatment, while the remainder provided on-water and onshore support (Carpenter *et al.* 1991). This support involved 1,400 vessels and 85 aircraft. Berthing vessels for up to 7,000 responders and support personnel initially included excursion boats and fish processing vessels, and US Navy transport ships. These were, in time, replaced by eleven housing camps on barges. A self-contained semi-submersible derrick barge provided the largest number of berths in a single vessel. This operation was sustained during summer months from May through mid-September 1989.

A similar, but much smaller marine-based

3 [http://www.arcticresponsetechnology.org/publications-data\(F3\)](http://www.arcticresponsetechnology.org/publications-data(F3))

response that involved more than 30 vessels was mobilised following the grounding and spill from the M/V *Selendang Ayu* in the remote and mountainous region of the Aleutian Islands of Alaska (Gallagher and Gudonis 2008) (See Annex E and Figure E.3).

For many years ice camps with air support have provided logistics bases for polar expeditions and research studies. Canada, for example, maintains a logistics organisation (the Polar Continental Shelf Program) to support northern remote area activities (<http://www.nrcan.gc.ca/the-north/polar-continental-shelf-program/polar-shelf/10003>). The Russian Arctic and Antarctic Institute has many decades of experience in creating and supporting remote ice camps throughout the Arctic, aided by extensive aircraft and ice-breaker resources. In terms of high ice class tonnage, Russia probably has greater resources

to support a major Arctic response (north of the Arctic Circle) or marine salvage operation than any other Arctic nation.

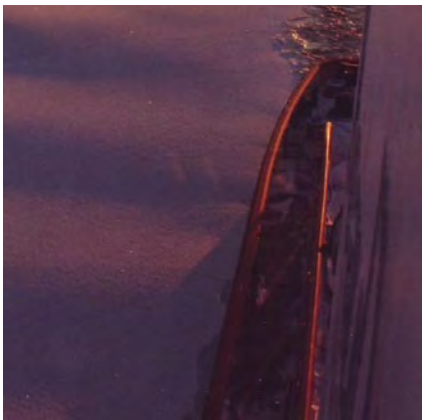
The Baltic Sea is significantly different from other areas covered in this Guide in terms of the level of resources and infrastructure that can be quickly brought to bear on an oil spill incident. The many highly developed neighbouring states maintain fleets of specialised vessels and aircraft that can assist in an emergency and HELCOM (the Baltic Marine Environment Protection, or Helsinki, Commission) and the Baltic Sea Action Plan provide a platform for cooperation and drills that greatly enhance preparedness in the region. There are a great many airfields with full instrument landing capabilities as well as extensive port facilities, rail and road infrastructure and staging areas throughout the Baltic region.

Part IV – Arctic Oil Spills in Ice and Snow: Behaviour, Fate and Effects

Chapter 1: Oil in Ice Fate and Behaviour

Chapter 2: The Effects of Spilled Oil in Ice- and Snow-Affected Marine and Coastal Arctic Environments

Chapter IV-1 Oil in Ice Fate and Behaviour



- Limiting spread
 - ▣ Reducing impact

 - **Net benefit:** increased time windows for
-

The following points outline how the behaviour of oil spills at low temperatures and in ice and snow can potentially both assist and hinder spill response in many situations. Related operational limitations and advantages associated with the presence of ice are covered in Chapter V-6. On the positive side, for example:

- Low air and water temperatures coupled with the presence of ice generally lead to much greater oil equilibrium thicknesses, reduced spreading rates and smaller contaminated areas.
- Evaporation rates are slower in cold temperatures and ice. As a result, the lighter and more volatile components remain for a longer time, thereby enhancing the ease with which the oil can be ignited.
- When ice concentrations preclude the effective use of traditional containment booms, the ice itself often serves as a natural barrier to the spread of oil. The natural containment of wind-herded oil against ice edges leads to thicker oil films that enhance the effectiveness of burning.
- With high ice concentrations (7/10 or more) most of the spilled oil (especially from a subsea blowout) would rapidly become immobilised and encapsulated within the ice.
- Oil encapsulated within the ice is isolated from any weathering processes (evaporation, dispersion, emulsification). The fresh condition of the oil when exposed at a later date (e.g., through ice management or natural melt processes) enhances the chances for effective combustion.
- The fringe of landfast ice common to most Arctic shorelines acts as an impermeable barrier and prevents oil spilled offshore at freeze-up from entering and impacting sensitive coastal areas.

At the same time, there are significant response challenges related to the unique aspects of oil behaviour in ice and snow, including:

- Lack of oil spreading or flow within often slush and brash-filled leads and openings in the pack ice, making skimming operations extremely difficult and ineffective.
- Lower evaporation rates with thicker slicks on cold water or oil buried under snow for example, can lead to greater persistence but, given sufficient time, the final evaporated volume can still approach values observed in more temperate climates.
- Increased oil viscosity at low temperatures makes oil more difficult to pump, a condition exacerbated by the presence of slush or ice pieces. Pumps, valves, and hoses may fail in freezing temperatures.
- Lower sea states often associated with the presence of ice could lead to reduced rates of natural dispersion and require the addition of mechanical mixing energy to enable chemical dispersants to work effectively.
- Sensitivity of oil spreading in ice to subtle changes in floe geometry and ice coverage: the action of manoeuvring a vessel close enough to access the oil may create rapid spreading of the slick into much thinner, less recoverable films.
- Gelling of crude oils with pour points at or below 0°C.

a. Background

- A key overall observation from field experiments in ice, such as the SINTEF Oil in Ice JIP, is that the slower weathering in the presence of significant ice cover can extend the windows of opportunity and effectiveness for response operations such as burning and dispersant application (primarily due to reduced emulsification rates and associated water uptake).
- The presence of ice can significantly interfere or block the flow of oil to skimmers in a traditional boom containment and recovery system. At the same time, natural containment provided in higher ice concentrations, for example trapping oil in thick pools between floes or in wind-herded patches against ice edges, can provide opportunities for mechanical recovery with over-the-side brush skimmers.
- Our current state of knowledge of oil behaviour in ice is mostly limited to observations in normal sea ice formed from seawater offshore with high starting salinities. The Baltic Sea is characterized by brackish ice and frequent freeze/thaw cycles through the winter. The resulting internal ice structure is different from regular sea ice with much smaller brine volumes. This lower porosity could slow or delay the process of natural oil migration through ice in the spring, observed in previous Arctic experiments. Chapter III-2b summarizes some key physical differences between Baltic ice and Arctic sea ice.
- The benefits of natural containment in high ice concentrations also provide similar benefits in terms of ISB potential.
- Any decision on which strategy to use in a given situation would need to consider issues such as permits and approvals, waste disposal, proximity to populations etc.

The behaviour of oil in ice is complex and difficulties in modelling the physics of ice growth, movement, and deformation on scales of metres or tens of metres are magnified when the details of oil behaviour are added. Fortunately, significant background literature exists on oil-ice interaction based on studies over the past 40 years: Dickins and Fleet (1992) and SL Ross *et al.* (2010) provide overviews of key studies (NRC, 2014).

Our understanding of the effects of Arctic conditions on oil spill behaviour and fate has increased significantly over the past decade (e.g., Gjøsteen *et al.*, 2003; Buist *et al.*, 2009; Brandvik and Faksness, 2009; Dickins *et al.*, 2008). The EPPR report “Behaviour of Oil and other Hazardous and Noxious Substances in Arctic waters” (BoHaSA) project, carried out by SINTEF for the Norwegian Coastal Administration, gathered and synthesised the current knowledge and expertise on the behaviour of oil and other hazardous and noxious substances (HNS) that might be released into Arctic waters as a result of a ship-source incident, an incident during oil or gas exploration and production, or an incident involving the spillage of oil or HNS stored on land (Singaas and Lewis, 2011).

Much of the existing knowledge concerning oil behaviour in ice derives from meso-scale and relatively small (less than 50 m³) field experiments (e.g., Norcor, 1975; Singaas *et al.*, 1994; Buist *et al.*, 2009; Sørstrøm *et al.*, 2010), which show that the processes of evaporation, dispersion, and emulsification are all significantly retarded in ice leads and openings between floes. Wave damping, limitations on spreading dictated by the presence of sea ice, and temperature appear to be the primary factors governing the observed change in weathering rates compared with spills in more temperate environments.

The following overview provides highlights of experience gained from experimental spills and other research in laboratories, tanks, and basins over the past four decades. Dickins (2011) summarised the behaviour of oil in ice derived from these findings and from direct observations from large-scale field trials dating back to 1972 (e.g., McMin, 1972; Nelson and Allen, 1982; Norcor 1975; Dickins and Buist, 1981; Buist and Dickins, 1987; Brandvik

et al., 2006; Dickins *et al.*, 2008; Sørstrøm *et al.*, 2010).

The behaviour of oil in ice depends greatly on the oil properties and discharge parameters and the scenarios. Discharges can span the range from subsea batch releases (e.g. marine pipeline rupture), subsea continuous releases (e.g. subsea blowout, chronic sunken vessel or pipeline leak), surface blowouts and tanker accidents (Chapter III-1).

Light crudes and condensates would quickly surface through slush and brash ice whereas heavy fuel oil can remain in suspension within the thick accumulations of slush common during freeze-up conditions and in leads through much of the winter in converging pack ice. Oil density and turbulence in the upper water column are the main factors governing the degree of oil incorporation in porous developing ice forms (slush, grease and frazil). The oil viscosity also controls the tendency for oil to break down into suspended particles. Heavier fuel oils can remain suspended at depth as larger, denser oil particles in slush and brash ice. This behaviour was observed during the well-documented *Kurdistan* tanker incident in March 1979 off the Canadian East Coast (Vandermeulen and Buckley, 1985).

b. Weathering

The physical and chemical changes that spilled oil undergoes are collectively known as ‘weathering’.

Weathering rates play a major role in determining the available windows of opportunity for different response strategies. For example, dispersant applications become much less effective as the oil spreads and as oil viscosity increases. Because oil viscosity can increase very quickly in open water, the time available for using dispersant can be very short – hours to days. In a similar fashion, if mechanical collection methods are employed, the type of pumps or skimmers used may need to be changed as the oil weathers and the viscosity rises. In situ burning becomes more difficult and requires a greater starting oil thickness as the oil emulsifies and weathers.

Weathering begins the moment the oil is released from its container, whether a pipe-

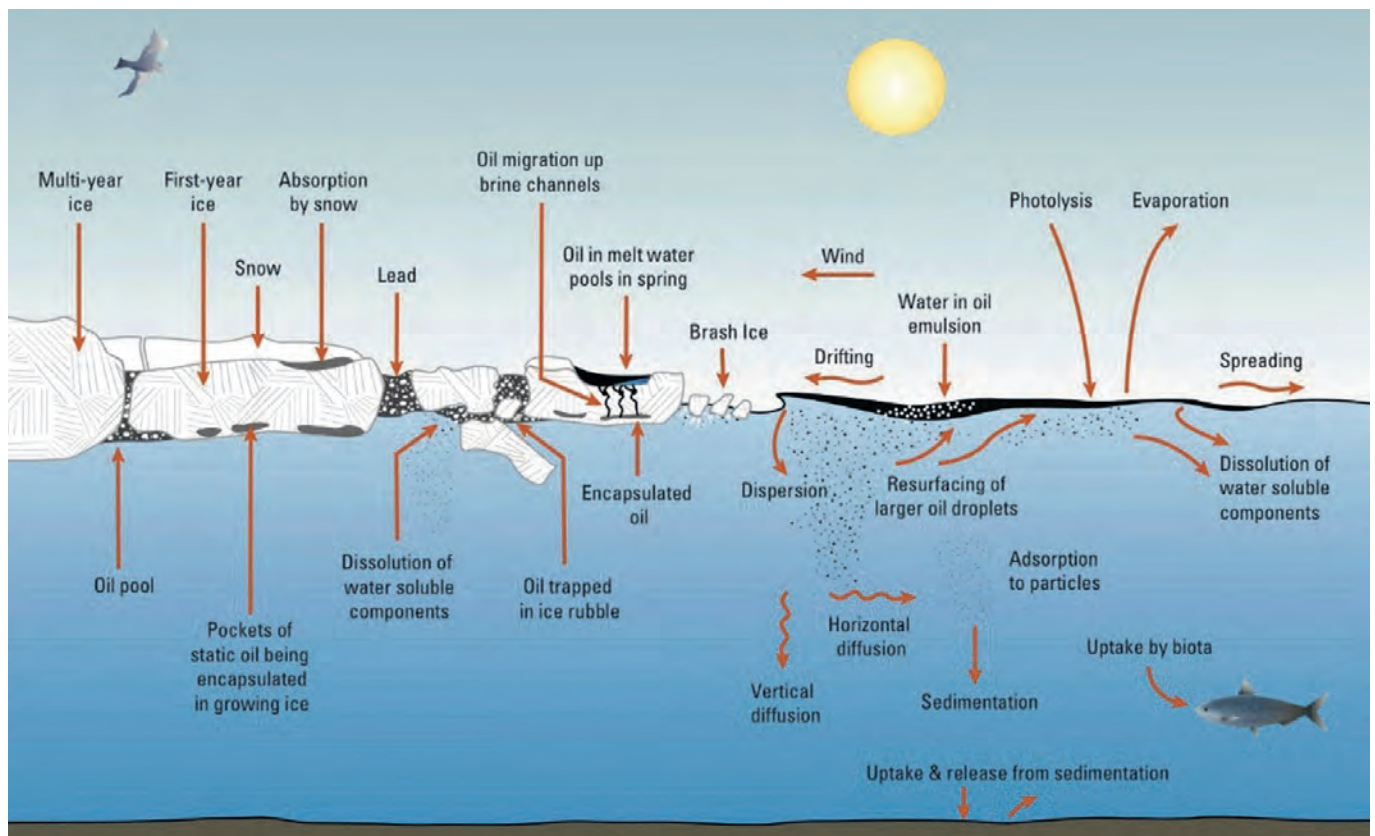


Figure IV-1.1 *Weathering Processes in Ice and at the Ice Edge* (Source: National Research Council, 2014 adapted from Allen and ITOPF) Note: this diagram shows the different processes in a range of potential Arctic and cold water environments from solid ice cover, very open pack ice and the open sea. The discussion in this guide focuses on the left side of the diagram and through to the ice edge transitioning to the open sea.

line, tank, or vessel, through the various processes of:

- Evaporation
- Emulsification
- Dissolution
- Dispersion
- Biodegradation
- Oxidation
- Sedimentation

Although the individual processes causing these changes may act simultaneously, their relative importance varies with time. Together, they affect the behaviour of the oil and determine the ultimate fate. The different weathering processes controlling the fate of spilled oil in water and ice are displayed graphically in Figure IV-1.1 (NRC, 2014). Spreading, evaporation, dispersion, emulsification and dissolution are most important during the early stages of a spill, whereas oxidation, sedimentation and biodegradation are longer-term processes, which determine the ultimate fate of oil. Physical factors dramatically influencing the rate of weathering include temperature, winds, waves and the presence of ice.

The presence of ice implies low air and water temperatures and a relative lack of waves, all factors that combine to significantly reduce the rates of evaporation, natural dispersion and emulsification. Photo-oxidation of spilled oil would not be significant during this time.

The rate of evaporation of oil is partly controlled by slick thickness. As such, the thicker oil slicks found under freezing conditions undergo evaporation at a comparatively much slower rate (versus open water). Snow adsorbing into surface oil and eventually covering the oil adds an additional resistance to evaporation. Ultimately, however, oil exposed on the ice surface, even after being covered with snow, loses about the same amount to evaporation as it would on water in more temperate waters.

The evaporative loss of a light oil under three different ice coverage levels (open water, 30% ice coverage, and 90% ice coverage) at various current and wave height conditions with different air temperatures (-15 to about -5°C) was studied by Brandvik and Faksness (2009). They reported that evaporative loss was estimated to be 30% for open water, 25% for the lighter ice coverage, and 19% for the

heavier ice coverage, due to differences in oil film thicknesses.

The formation of water-in-oil emulsions (also known as “mousse”) and the natural dispersion of oil slicks are both processes driven by wave action mixing the oil slick. Wind waves (as opposed to swell) are very effectively damped by a broken ice field with concentrations over 6/10 (60% coverage), but can still cause significant problems in deploying equipment near the edge of an ice field and potentially several miles into the ice in lower concentrations. The content of water in the surface oil leading to emulsification is greatly slowed by the presence of ice in higher concentrations (Figure IV-1.2).

Natural dispersion of oil slicks (the process of breaking waves that force oil droplets into the water column, the smallest of which do not resurface and remain in the water) is similarly unlikely when the presence of ice restricts any significant wave action.

Gelling is an important oil-property change that may take place with oil spilled on ice in winter. Gelled oil is a semi-solid material that subsequently evaporates slower than fresh oil, and may develop a non-sticky, waxy surface coating. Oils that may be fluid in warmer temperatures can gel when the ambient temperature falls below their pour point (defined as the temperature at which sufficient waxes have precipitated from solution in the oil to prevent it from flowing under gravity). Annex A provides information on pour points for different crude oils and petroleum products.

c. Movement and Drift Rates

Oil trapped within pack ice over 6/10 concentration tends to move with the ice at ~3-5% of the wind speed with a turning moment ~20 to 30 degrees to the right in the Northern Hemisphere due to the Coriolis effect. Oil in more open drift ice can move at different rates from the ice, for example, thick rough floes with large sails and keels experience different driving forces from currents and winds than an oil slick on the surface or on a smooth thin ice sheet. It is not unusual to see an iceberg or old floe moving against the wind in response to currents at depth (Photo C in Fig. III-2.9).

Winter under-ice currents in most Arctic near shore areas are not sufficient to spread spilled oil far beyond the initial point of contact with the ice under surface. Exceptions may be in fjord-like areas with strong tidal currents or in narrow Arctic straits such as Kara Gate. Several studies have determined that, with roughness values typical of undeformed first-year sea ice in mid-winter, the threshold current speed needed to initiate and sustain movement of an oil lens or pool along the ice under surface is approximately 20 cm/sec or ~0.5 kt. Refer also to a related discussion of trajectory modelling in Part IV-3 below.

d. Spreading

The most dramatic difference between spills in ice and open water is found by comparing the spreading behaviour. As a general rule of

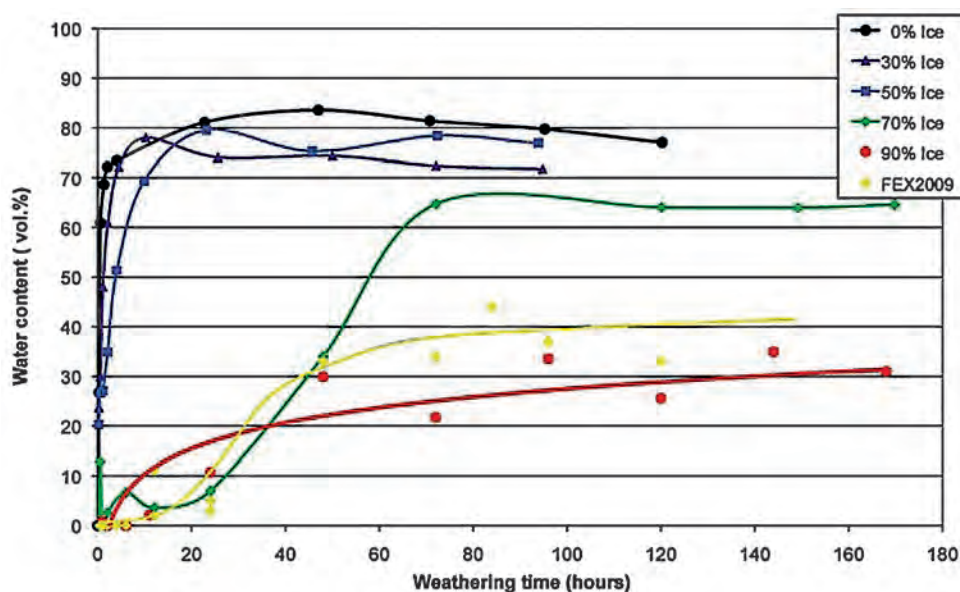


Figure IV-1.2 Comparison of water content vs. weathering time for five different ice concentrations (0 to 90% coverage) using data from tank tests. FEX 2009 refers to field validation during trials in the Norwegian Barents Sea (Source: SINTEF).



Figure IV-1.3 Oil stopped from spreading by slush in a lead (Photo: D. Dickins).

thumb with a spill in open water, about 90% of the oil covers only 10% of the spill area – this so called “thick slick” is typically in the order of a tenth of a millimetre thick (100 μm). The remaining 10% of the oil covers a much larger area (hundreds of times) in the form of a “sheen” (<1 μm thick). Large trailing sheens can look dramatic from the bridge of a vessel but actually represent very small volumes of oil.

This thick versus thin slick distinction is generally valid for spills in open or very open drift ice less than 4/10 concentration. In closer, more concentrated pack ice, slicks may never reach their natural equilibrium thickness as spreading is slowed or stopped by the presence of ice floes in close contact or slush. The containment effect of slush in the water between floes is shown dramatically in Figures



Figure IV-1.4 Oil in slush between floes in 4-6/10 pack ice (Buist and Dickins, 1987).

IV-1.3 and 4 during a deliberate field release in pack ice off the East Coast of Canada in 1986 (Buist and Dickins, 1987).

Table IV-1.1 compares the predicted final areas and thicknesses covered by a 1,600 m^3 (10,000 bbl) batch crude oil spill on open water, under solid sea ice, and on smooth sea ice with and without snow. It is clear that the spreading of oil is greatly reduced by ice and snow and the resulting slicks are much thicker than those on water. This reduction in spreading has far-reaching implications (mostly positive) in terms of extending response times, limiting the oiled area, and retaining multiple response options for a longer period, thereby extending the windows of opportunity to implement a given strategy.

In pack ice, the degree of natural containment depends greatly on the ice concentration

	Open Water	Under Solid Mid-Winter Ice	On Smooth Ice	
			Ice	Snow
Final avg. oil thickness (mm)	0.016	40 to 90 ⁺	3	40
Final area (ha)	10,000	7 to 70 [*]	50	4

Source: Adapted from original table in SL Ross *et al.*, 2010. Revised table with modified thickness and area under solid ice (see note below) based on results by Wilkinson *et al.*, 2007 published in Dickins (2011).

⁺ The maximum pool depth under ice depends on the depth of the under-ice depressions, which grow deeper as the ice grows over winter.

^{*} The range of areas reflects the variable processes of oil spreading under ice. The final contaminated area depends on both the available volume of under-ice depressions and how they fill with oil: a point source subsea release of oil beneath undeformed fast (static) first-year ice may flow outward under the ice by only filling interconnected under-ice depressions (after Wilkinson *et al.* 2007), but a point source subsea release beneath a moving undeformed ice sheet may result in all the available under-ice depressions filling, depending on the flow rate, ice velocity and gas volumes.

Table IV-1.1 Spreading comparison for a 1,600 m^3 (10,000 bbl) crude oil spill.



Figure IV-1.5 View of the main 59 bbl (7 cubic metre) spill in 8/10 pack ice while being discharged during the 2009 SINTEF Oil in Ice field experiment in Svalbard, Norway. The effectiveness of the closely packed floes in trapping and containing the oil in this situation is clearly apparent. Very little additional spreading occurred in subsequent days (Photo: SINTEF).

and other variables. The relationship between spill area and ice concentration is not linear at low concentrations. At some point in open to very open drift ice with concentrations less 6/10, the ice no longer contains the oil and the spreading rates quickly begin to approach open water rates (Dickins and Buist, 1999).

e. Encapsulation, Migration and Release

Oil spilled under young ice would likely become encapsulated by new ice quickly growing beneath the oil within 12 to 24 hours, based on extensive observations of the behaviour of oil spilled under ice at different times during the Arctic winter (Dickins and Buist, 1981; Dickins and Buist, 1999). Under very thin new



Figure IV-1.6 Cut out of a large ice block removed from an under ice spill on the North Slope of Alaska, showing the encapsulated oil layer with new ice growth beneath the oil (Photo: A. Allen).

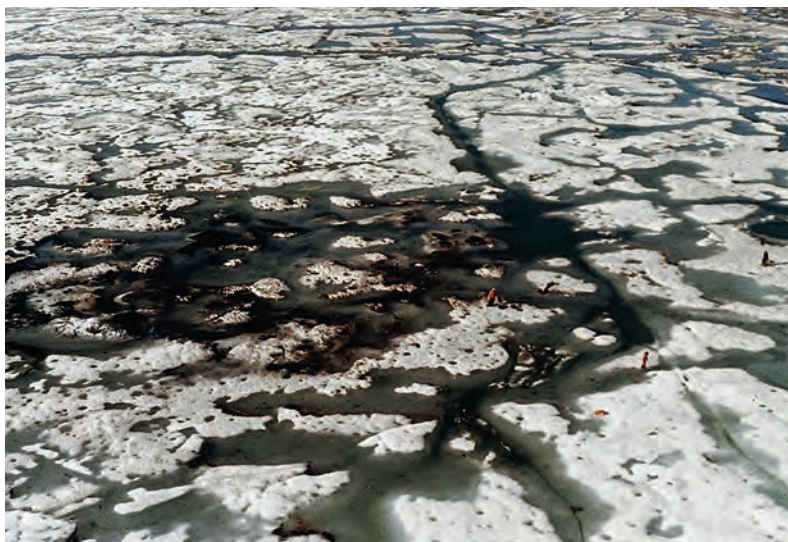


Figure IV-1.7 Low-level aerial view in June 1980 showing oil on surface melt pools after migrating from trapped oil layers within the ice after a series of under-ice simulated blowouts during the winter of 1979-80, McKinley Bay in the Canadian Beaufort Sea (note people on the ice for scale) (Photo: D. Dickins).

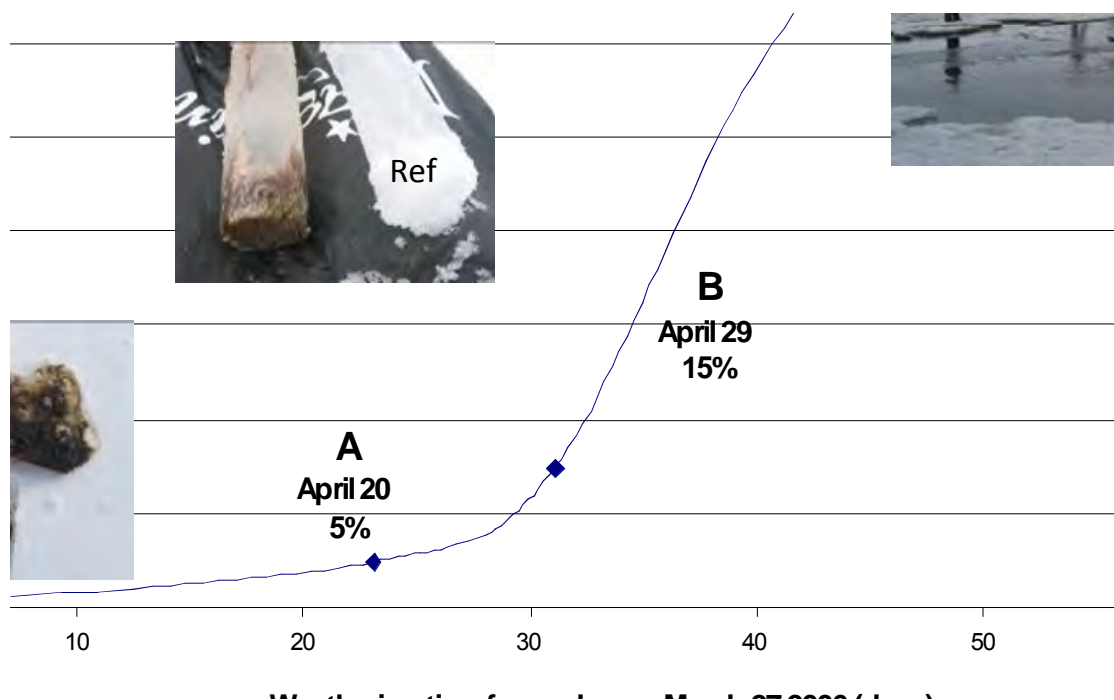
ice, less than ~10 cm oil may migrate quickly to the surface but as the sheet cools and becomes less porous in November the oil will remain trapped as a discrete layer, remaining relatively static until the onset of warming temperatures in late March and April. Even in mid-winter with 1.5 m of ice, a layer of new ice would form beneath the oil under within 48 hours (Dickins 2011).

Oil spilled under ice late in the winter (May in many Arctic regions) is unlikely to become encapsulated as the ice growth rate slows. Once the brine starts to drain from the ice sheet in the spring, the oil utilises the now vacant brine channels as a pathway to migrate vertically within the sheet. By early June (in a Canadian Beaufort Sea environment for example), over 80% of the oil can be found on the surface floating on melt pools (Fig. IV-1.7).

Oil originally spilled beneath growing sea ice appears at the ice surface in the spring as close to fresh crude with all of the light components attached. Once exposed in this manner, the oil is subject to normal evaporative loss: up to 30-35% by volume in many cases. These high rates reflect the effects of solar heating of black oil: oil film temperatures on ice melt pools can exceed +10°C even in near-freezing air temperatures (Norcor, 1975).

The oil floats on the melt pools on top of the ice as the sheet deteriorates (Fig. IV-1.7) Winds tend to concentrate the oil in thicker patches at the edges of these pools where it can be readily ignited and burned with high over-

Figure IV-1.8 Progression of oil migration through the ice following a spill of 28.5 bbl (3.4m³) under ice at Svea, Svalbard in 2006. Inserted pictures show oil on top of snow (A), cores drilled through the ice to quantify oil captured in the ice (B + C) and the final melt pool (D) (Source: Brandvik et al., 2006).



all efficiencies. The oil that surfaced in 2006 (graphed above) was burned with an efficiency estimated at 96% after lying exposed on the ice surface for over one month and being 27% evaporated (Brandvik et al., 2006).

There are situations where the oil could migrate very slowly, if at all, such as when the spill is naturally dispersed as fine droplets under the ice during a subsea blowout with large volumes of gas or situations where oil is spilled under low salinity or brackish ice. In those cases, it may be necessary to wait for the ice surface to melt down sufficiently to expose the trapped oil at the surface (Dickins 2011). Refer to the earlier summary of some physical differences in ice structure between brackish Baltic ice and Arctic or Polar sea ice. (Chapter III-2b)

As the remaining relatively thin ice quickly melts and disintegrates over a 3-4 week period (June to early July for example in the Canadian Beaufort Sea, earlier in lower latitudes), residual oil still trapped in the porous ice and any oil left on the ice surface would be released to the water as sheens, broken thin oil films, or patches.

Gelled oil may be discharged into the cold water as thicker, non-spreading mats or droplets. Once exposed to significant wave action, most of the residual oil will begin to emulsify and naturally disperse at sea.

f. Spreading and Weathering of Spilled Oil in Snow

This section discusses the spreading and weathering of spilled oil on snow in both a marine and coastal/shoreline context. The behaviour of oil spilled from the surface onto a snow cover is essentially the same, whether the snow cover happens to be on the surface of landfast or drifting pack ice or on the shoreline itself.

The definitive work on the modelling of oil spills in snow by Belore and Buist (1988) built on a number of previous investigations and produced process equations to predict the fate and behaviour of oil spills on land or ice in or under snow. Equations were developed for (a) the gravity-viscous spreading regime; (b) oil infiltration into snow; (c) horizontal spreading on an impermeable surface beneath a snow cover; and (d) oil evaporation beneath a snow cover. This theoretical work provides an understanding of the mechanisms of percolation and weathering, that is, evaporation, processes for oil in snow.

Evaporation is the single most important weathering process for oil trapped in snow. One study on a medium crude oil measured evaporation rates exceeding 50% by volume after 6 days exposure at 0°C (10 knot wind) (Buist et al., 2009). Buist (2000) states that, "Although the evaporation of oil on ice in winter is slower, eventually the oil (even that covered by snow) will evaporate to approximately

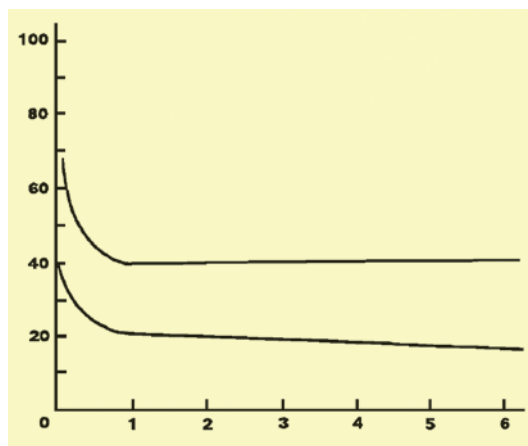


Figure IV-1.9 Sorption capacity of snow over a 6-day period (y-axis) as the % by volume (x axis) after sample melt, for diesel (lower curve) and Prudhoe Bay crude (upper curve) oils (after ACS, 1999 – reproduced in Alaska Clean Seas 2013).

the same degree as it would if spilled on the water in summer”. The limited available test data show that oil covered by snow would continue to evaporate, albeit at a lower rate than oil directly exposed to air. The actual rate of evaporation is a complex function of a number of variables including snow diffusivity (related to the degree of packing), oil properties, air temperature, wind speed, and the thickness of the oiled layer.

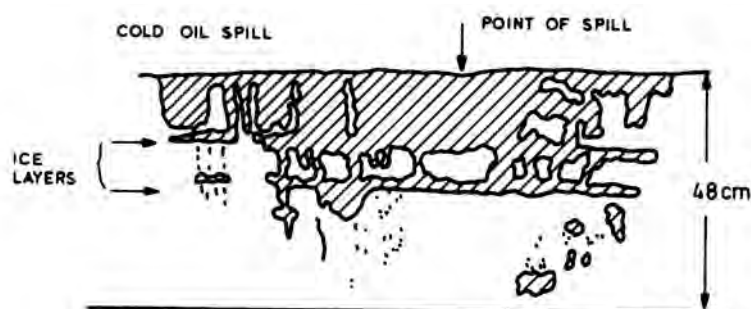
In terms of the absorbent properties of snow, a value of 20% is quoted as being commonly used as the “static porosity” for oil spill planning (for example, ACS, 2013). The ACS curves were originally developed a series of experiments in Anchorage (1978), where 0.03 bbl (4 litres) of crude oil and diesel oil were poured into 30 to 45 cm of loose, fresh snow. The site remained undisturbed by wind or new snow, and samples were taken over a period of 5 days (A. Allen, pers. comm., June 2003). These curves (Figure IV-1.9) can be applied to spills that have been allowed

to spread to an equilibrium thickness over a level surface without lateral or vertical containment. The specification of lateral containment is important because with the presence of barriers to spreading (ice ridge features, man-made berms, etc.) the interruption to natural spreading would lead to a much higher percentage oil content (% of melted snow sample by volume). The ACS sorptive capacity curves originally developed by Allen in 1978 refer to a situation where the oil penetrates into the snow both vertically and laterally. This outcome results from a balance between gravity and viscous/inertia forces in the absence of any lateral barriers to spreading. In this natural situation on a level surface, the final sorptive capacity is far less than the potential capacity at saturation (where most of the pore spaces or air pockets in the snow are filled with oil). Close-to-saturated oil in snow condition will only be achieved in a setting where horizontal migration is restricted.

Results from Experiments and Spill Case Histories Mackay *et al.* (1975)

This study involved (i) a set of laboratory investigations of oil flow and oil-ice interfacial tension through a refrigerated snow column using Norman Wells and Alberta crudes, and (ii) three summer/winter field trials with “cold” (-5°C) and “hot” ($+17^{\circ}\text{C}$) oils in natural snow. In one study with 1.5 bbl (0.18 m^3) of cold (0°C) Alberta crude on a 20cm snow cover in winter “the snow acted as an excellent absorbent” and the oiled area was only one-eighth as large as that from a similar spill study conducted in the summer months. In a separate study with 5.2 bbl (0.63 m^3) of cold

Figure IV-1.10 Cross-section sketch and photograph of cold oil spill on snow. The oil drained through the surface snow and accumulated above the layers of ice (from Mackay, 1974).



(0°C) Norman Wells crude on a 50- to 60-cm snow cover in winter, within 30 hours the oil had penetrated in to the ground in places. Figure IV-1.10 from this field trial shows the pattern of cold oil in a highly crystalline snow with several icy layers; the oil drained rapidly but accumulated above the ice layers and spread over a 10,000 cm² area. The most significant results were that snow is far from uniform in character and can include layers of solid ice that act as impermeable or semi-permeable barriers to vertical and horizontal oil movement.

Johnson *et al.* (1980)

Field experiments on a low-angle (7 to 8%) tundra surface with a 45-cm snow cover were conducted using heated (+57°C) Prudhoe Bay crude oil. The release involved 63 bbl (7.6 m³) over a 45-minute period in February (air temperature -5°C). The oil melted holes in the snow and then moved downslope under the snow cover and within a moss layer without disturbing the snow surface. The leading edge of the oil reached 18 m down slope within 24 hours but then remained stationary and did not remobilise until the spring melt in May, after which it gradually moved a further 17 m downslope.

Bech and Sveum (1991)

A series of field experiments were conducted using crude oil and diesel released in 1.0 m³ (8.4 bbl) batches with air temperatures ranging between -4.5 and -18°C to observe the spreading characteristics with natural snow on horizontal and gently sloping surfaces. Eight experiments were conducted on a horizontal surface where the snow depth was a relatively uniform 60 cm and rested on impermeable ice. The oil was released both onto the surface of the snow cover and on the ice under the snow. In these horizontal slope experiments where the oil was released under the snow, 10 cm above the ice surface, the oil initially spread vertically and then horizontally. After the release was completed, the oil drained vertically to create a generally circular oiled area

that covered 28 and 33 m² for the crude and 64 and 72 m² for the diesel. The spread of the oil released onto the snow surface was non-radial due to “variations in snow topography and porosity”, and the oiled areas were 14 and 23 m² for the crude and 60 and 118 m² for the diesel. Spreading rates were found to be a function of the spill rate, and the size of the oiled area was a function of the oil and snow properties. Two experiments were conducted on a land site with an approximate 30° slope where the snow depth varied between 30 and 150 cm but no data were presented. The study provides some general information on oil behaviour and on spreading rates.

Allen (1978)

Nearly 190 bbl (22.7 m³) of No. 2 diesel spilled from a storage tank in Nome, Alaska in March with air temperatures between -18° and -35°C. The thickness of the drifted, loose, dry, granular snow near the source varied from 30 to 60 cm and was less than 30 cm over open ground where drifting was less pronounced. The oil saturated the snow and migrated 3 to 4 metres down slope through the snow on to and under adjacent river ice. The snow near the source was sufficiently compacted to form effective barriers or berms that temporarily contained oil on the snow surface. Oil that had migrated through the snow adjacent to the tanks penetrated the dry porous soils. Oil was recovered from the soil each day by placing clean fresh snow on an approximately 50m² oiled area in the evening and then removing saturated oiled snow the next day and replacing that once more with clean snow.

Carstens and Sendstad (1979)

Approximately 1,090 bbl (130 m³) of diesel leaked from a storage tank in Spitzbergen in April over a 26-day period before the leak was discovered. Adjacent to the tank, the oil spilled onto a snow surface and migrated a distance of 200 m downslope to the toe of the snow drift. The residual oil content in the drained snow through which the oil had migrated varied between 0.6 and 2.8 % by volume.

Chapter IV-2 The Effects of Spilled Oil in Ice- and Snow-Affected Marine and Coastal Environments

- The behaviour and fate of released petroleum is an important consideration in understanding the potential effects of released petroleum and in evaluating the potential OSR options in the arctic.
- The projected environmental damages, including acute and chronic toxicity responses, are affected by the choice and application of each OSR option (including the option of natural recovery).
- Spreading and weathering of petroleum in the arctic is complex, influenced by factors such as water temperature, local currents and wind conditions, the presence and absence of seasonal and multi-year ice, effects of pressure in deep water environments and seasonal changes in salinity during the Arctic spring.
- The presence of ice has been shown to significantly slow the rate of spreading and weathering of surface oil, as well as affecting predictions of spill locations and trajectories.
- There are concerns that physiological, morphological, and behavioural adaptations of Arctic species may alter their sensitivity to petroleum and treated petroleum. Recent research shows that indigenous cold-water species have sensitivities and resilience to oil exposure similar to non-Arctic species from temperate waters.
- In general, the winter months constitute a time of less biological activity than the spring or summer when for example, vast numbers of birds and marine mammals congregate at the ice edge in many arctic areas.
- Shorelines in areas with persistent ice cover are typically protected from direct oiling in winter by a fringe of fast ice, which lessens the likelihood of significant immediate impacts.
- There are specialised and unique species that live under and within ice, including larval forms of important water-column species. Although the communities under the multi-year ice are becoming better known, the ecological importance of the annual undersea ice biota is less understood.

An in-depth treatment of the full range of possible environmental impacts as a result of an oil spill offshore and in coastal waters is beyond the scope of this Guide, but the following cross section of material highlights some key concerns and issues on this topic drawn from a number of recent sources:

- Arctic Monitoring and Assessment Program (AMAP)- Arctic Council (2008)
- Lee et al. (2011) in material prepared for the Canadian Government Arctic Offshore Drilling Review

AMAP (2008) notes that “Some Arctic animals are particularly sensitive to oil because it reduces the insulating properties of feathers and fur and they can quickly die from hypothermia if affected. This is the case for seabirds, including eiders and other sea ducks, and also polar bear and seal pups. Concentrated aggregations of birds and mammals, often in confined spaces such as leads and polynyas and at the ice edge (for example, the Bering Sea

and Lancaster Sound) increase the risk to the animals in the case of an oil spill. Even small spills can have large consequences if they occur where marine birds are concentrated. Other potential problems from released oil include the transfer of oil to nests by sea birds landing on oil slicks and the ingestion of oil by animals while preening. This can lead to death or other biological effects both in the short and long term. Chronic seepage of residual oil after a spill can affect the entire food chain in an area because hydrocarbons are taken up by bottom feeding invertebrates, which can then end up as prey for sea birds and other animals, causing effects higher up the food web. Arctic animals are particularly vulnerable to spills in the spring and summer when animals aggregate in large numbers to breed, nest, bear young and molt.”

Lee et al. (2011) summarises a number of key aspects concerning the effects of oil on ecosystems affected by the presence of an ice cover. “A multitude of biological effects have been observed in toxicological studies with oil

with a range of biota covering multiple trophic levels. In the Arctic, seasonal aggregations of animals, such as marine mammals in open areas of sea ice and at the ice edge, seabirds at breeding colonies or feeding sites, or fish at spawning time may be particularly vulnerable to oil spills. For example, an oil spill in the spawning areas of polar cod could severely reduce a year-class of the population”.

There has been a shift in biological effect studies from ‘acute’ studies focused on mortality as the end-point to that of ‘chronic’ responses associated with much lower exposure levels and their effect on the long-term health, growth and reproduction of the target organisms. With the implementation of ecosystem-based management by regulators, future studies should include consideration of biological effects on population and on community structure and function. Such studies are necessarily very regional or geographically local in nature due to the great diversity and frequently dynamic character of marine communities. In addition, biological effects should be considered in the context of vulnerability and timing. There are many areas which have low species concentrations for long periods each year and others where there exist high concentrations of certain species but which are vulnerable only during narrow time and spatial windows.

Interpretation of the data collected for environmental risk assessments is challenging as the exposure conditions in past scientific studies (e.g. dosage and exposure time) are frequently outside of the range observed in the field following actual spill events. Furthermore, as illustrated by a case study following the *Exxon Valdez* spill in Prince William Sound, Alaska, a consensus on the levels of environmental impacts have not been achieved due to a number of confounding factors including different approaches to natural resource damage assessment, the lack of pre-spill baseline information, and reported high levels of natural variation in population numbers and community structure” (Weins, 2013).

The United States Geological Survey (USGS) 2011 report on arctic science concluded that the effects of climate change as well as marine activities should be considered

when evaluating potential impacts of, for example, expanded shipping or expanded oil and gas exploration and development. The following points are extracted as examples of general application to the entire Arctic (recognising that many of the conclusions are specifically targeted towards conditions on the Alaska Outer Continental Shelf):

- Climate change also would impact organisms in the Arctic (including fish, birds, whales), pinnipeds (ice seals and walrus), and polar bears in many different ways, including through the warming of Arctic waters from sea-ice declines and from changes in the food chain, notably from the potential effects of acidification of the Arctic Ocean.
- Information on the physical oceanography (such as circulation processes and wind) is critical for oil-spill modelling, oil-spill response, and cleanup efforts, as well as for understanding biological resources. Outputs from such trajectory models also influence ecological effect analyses, as well as spill contingency planning and real-time response considerations.
- Current information and recent baselines developed for different components of the Arctic ecosystem should be supplemented with ongoing monitoring in order to understand the changes in the ecosystem and monitor its health. Information is needed on all levels of species, from phytoplankton, microbes, and zooplankton, to fish and birds, to marine mammals. It is important to include not just those species that live in the Arctic year-round, but also migratory species.
- The subsistence community and culture are an essential component of the Arctic and all of the issues studied in this report would have an impact on these people and their way of life. To predict with any degree of accuracy, the future of Arctic subsistence, with or without energy exploration and development, would require a greater understanding of the potential changes in local environments and ecologies because subsistence patterns closely correlate to these factors. Thus, subsistence patterns are vulnerable to the effects of climate change

and anthropogenic development (whether it be oil and gas development, shipping, tourism, or another). Additional information is needed to determine the potential hazard to native subsistence livelihoods from oil and gas exploration and development, since such development can impact all parts of the spectrum from the specific subsistence animals themselves through their food chain and ecosystem.

- Recent studies following the Macondo oil spill have shown the importance of characterising not only the indigenous microbial communities in benthic sediments, but also those in the water column. In particular, Hazen and others (2010) reported natural biodegradation of the dispersed oil plume in deep water. Because the microbial communities appeared to rapidly adapt, as reflected in hydrocarbon-degrading genes, in response to the oil plume, the researchers concluded that there was potential for intrinsic bioremediation of oil contaminants in the deep sea. As such, these communities may have an important role in the fate of hydrocarbons in the Gulf of Mexico (Hazen and others, 2010). Analogous studies of indigenous microbial populations in the Arctic are warranted to gain a bet-

ter understanding of the potential for these processes to naturally attenuate an Arctic oil spill.

The population of in and under-ice algae and biota (also known as the pontic community) is recognized as a key part of the food web in Arctic regions. Granskog (2006) points out that these ice-resident microscale biota are also an important feature of the Baltic ecology.

“As in Polar sea ice, the Baltic ice can harbour rich biological assemblages, both within the ice itself, and on the peripheries of the ice at the ice/water interface. Much progress has been made in recent years to study the composition of these assemblages as well as measuring biogeo- chemical processes within the ice related to those in underlying waters. The high dissolved organic matter loading of Baltic waters and ice result in the ice having quite different chemical characteristics than those known from Polar Oceans. The high dissolved organic material load is also responsible in large degree to shape the optical properties of Baltic Sea ice, with high absorption of solar radiation at shorter wavelengths, a pre- requisite for active photochemistry of dissolved organic matter.”



Part V – Marine Strategies and Response Options for Oiled Ice and Snow

Chapter 1: Background and Introduction

Chapter 2: Detection, Delineation, Monitoring and Tracking

Chapter 3: Mechanical Containment and Recovery

Chapter 4: Dispersion and Oil Mineral Aggregates (OMA)

Chapter 5: Controlled Burning

Chapter 6: Summary of Marine Spill Response Effectiveness

- A primary objective of an effective marine response is to select and implement a combination of response techniques that would be most effective in minimising overall short and long term impact, including preventing oil from reaching the shoreline and sensitive areas.
- For the Arctic and other ice-covered marine environments, this approach helps to focus discussions on the relative short-term and long-term impacts on key ecosystem components and those resources of greatest subsistence and cultural value to indigenous peoples and residents (core issues in a Net Environmental Benefit Analysis – Chapter II-4).

Basic response strategies for spills in ice include the same general suite of countermeasures seen elsewhere in the world. They include:

1. Mechanical containment and recovery utilising booms and skimmers in open water and very open pack ice, and skimmers extended from vessels directly into trapped oil pockets in heavier ice;
2. A combination of strategies to concentrate the oil and burn it *in-situ*. In ice-covered environments, these can involve: containment against natural ice edges without booms, fire resistant booms in open water or very open drift ice, and herding agents that can thicken and concentrate oil in open water and intermediate ice concentrations under non-freezing conditions;
3. Dispersants that disperse surface oil into the water column as small oil droplets with a target diameter of less than 100 microns. The goal is to dramatically increase the overall oil surface area on which microorganisms can act to effectively biodegrade the oil. Application can be from the air, surface (with both natural and induced mixing energy from propeller wash), or subsea (direct injection);
4. Detection and monitoring while potentially planning a later response (e.g. burning on ice in the spring); and
5. Natural attenuation through evaporation and dispersion (no deliberate response).

Emergency response is particularly challenging in ice-covered waters for a variety of reasons, including coping with the dynamic nature and unpredictability of the ice; the remoteness and great distances that are often involved in responding to accidental spills in the Arctic; the impacts of cold temperatures, ice and a harsh operating environment on response personnel and equipment; and the frequent lack of shore-side infrastructure and communications to support and sustain a major response effort (Arctic Council – AMAP, 2008). See also Chapter II-5.

After ensuring that there is no ongoing risk to human life, health, and safety, the first and highest priority is always to stop or reduce the discharge. In the case of a vessel accident, this may involve implementing a lightering operation, such as was conducted with the *Exxon Valdez* response, or applying conventional salvage techniques with temporary patches if possible to stem the flow of oil from damaged tanks or ruptures in the hull. In some cases, it may be necessary to seek a “safe haven” or refuge in protected waters to carry out these operations. Decisions and approvals to move a damaged vessel are complex and subject to multiple levels of government oversight at the national, regional, and local levels.

In case of loss of well control at an offshore rig or facility, a capping operation may seal off the well bore in a relatively short period of time (days to weeks) and stop the flow until a relief well can be initiated to plug and secure the well for the long term. Since the Macondo incident in 2010, the technology necessary to enable a rapid capping stack operation has advanced considerably. Much of this technology is applicable to marine areas with stable fast ice, including lakes and rivers with solid ice (e.g. Kara Sea and Beaufort Sea). Permits for future arctic exploration wells in North America could require the operator to have a capping stack system with necessary marine support on site or in close proximity for rapid deployment. There are significant challenges in applying this technology to wells on the continental shelf in relatively shallow water. In these cases, recently developed additional prevention measures, such as Chevron’s Alternative Well Kill System (AWKS), can potentially provide equivalent levels of risk reduc-

tion. These systems are designed to reliably shear large diameter casing strings and leave the well temporarily sealed to reliably last through the winter.

Chapter V-1 Background and Introduction

Strategies and techniques for dealing with oil in ice have been studied intensively in the United States, Canada, Norway, and Sweden. The resulting body of documentation and reports is extensive, taking the form of:

- Response manuals
- Specialised conference proceedings
- Industry programs
- Experimental spills
- Tank and laboratory tests

There are a number of dedicated Arctic spill response manuals or guides. Nearshore Arctic spill response strategies and tactics are developed in detail and are described in graphs and tables in a comprehensive tactics manual (ACS, 2013 Rev. 11). This manual (available in electronic form) covers all known techniques for recovering and removing oil spilled under or on the surface of solid ice as well as oil spilled into broken ice during the shoulder seasons of break-up and freeze-up. Although developed for the nearshore ice zone off the Alaskan North Slope, many of the ACS tactics are applicable to other Arctic areas with extensive areas of fast ice (e.g. Kara Sea, Canadian Beaufort Sea), as well as Arctic lakes and rivers with solid and broken ice cover (e.g. Ob River, Yenisei River) and areas in the Baltic with stable ice attached to skerries and islands.

EPPR (1998 and 2008 Rev.) developed a comprehensive field guide that covers all tactical aspects of oil spill response in Arctic waters, with a focus on shorelines and coastal areas. In addition, a guide covering response to spills on marine shorelines (including areas with ice and snow) was prepared by Environment Canada (Owens and Sergy, 2010).

Much of the knowledge gained about both the behaviour of oil in ice and the applicability of different response strategies to spills in

ice is derived from a relatively small number of large-scale experimental spills in Canada and Norway over the past 40 years. Two of the largest field experiments involving oil in landfast ice took place in the Canadian Beaufort Sea in 1974-75 and 1980 (Norcor, 1975; Dickins and Buist, 1981). The Norcor project involved eight spills of two different crude oils totalling 330 bbl (39m³), spilled under ice ranging in thickness from 43 to 180 cm. A later experiment in the same region simulated a sub-sea blowout by injecting compressed air and Prudhoe Bay crude oil under landfast ice (Dickins and Buist, 1981). Both of these spills were successfully removed from the marine environment by burning the oil on melt-pools following natural migration of oil to the surface.

Oil from a later experimental spill under solid ice on Svalbard was also burned with over 90% efficiency after lying exposed on the ice surface for over one month (Brandvik in Dickins *et al.* 2006) (Figure IV-1.8).

Field spills under controlled conditions in broken (pack) ice are limited to only four main experiments: a series of spills during a single trial over several days off the East Coast of Canada in 1986 (SL Ross and DF Dickins, 1987); an offshore test in Norwegian Arctic waters (Vefsnmo and Johannessen, 1994); and a series of relatively small spills (4 to 59 bbl, or 0.5 to 7 cubic metres) in pack ice to the East of Svalbard in 2008 and 2009 (Sorstrom *et al.*, 2010).

In the 1993 Norwegian test, a limited amount of oil was recovered with a rope-mop skimmer but problems were encountered in manoeuvring the vessel in close proximity without altering the oil distribution and in separating oil from ice and water in the recovered fluids. Two of the three discharges in the 1986 Canadian experiment were contained as thick patches in over 9/10 ice coverage and successfully burned with efficiencies ranging from 80 to 93%. Field spills in pack ice in the Norwegian Barents Sea in 2008 and 2009 successfully employed dispersants with mechanically-induced mixing energy, burning of herded oil, and burning oil mixed with ice in fireproof booms (Figures V-4.1 and V-5.1). Chapter V-5 provides a detailed discussion of burning, including potential negative effects such as particulates (soot) and CO₂.

A large number of tests in the US, Canada, and Norway have focussed on testing different skimmer designs in a wide range of ice conditions (Figure V-3.6). This research continued through the SINTEF JIP on Arctic Spill Contingency (e.g. Sorstrom *et al.*, 2010). At this stage any future improvements in mechanical recovery systems for ice environments are expected to be evolutionary rather than revolutionary (Chapter V-3).

Spills of opportunity in Canada (primarily on the East Coast) and the Baltic Sea, as well as a number of large-scale field experiments in Canada and Norway, have afforded an opportunity to evaluate and attempt a mix of response strategies in ice involving over-the side skimmers (rope-mops, and brush-bucket), dispersants, and in-situ burning in ice, booms and herding agents. Lessons learned from this extensive body of research and experience is discussed in Chapters V-3, V-4 and V-5, covering different response strategies.

The need for approvals before using response strategies such as dispersants and burning is a key issue in many jurisdictions. In an effort to deal with many of the environmental issues surrounding the application of these techniques, the ART JIP is currently engaged in a series of projects aimed at exploring such topics as dispersed oil resurfacing in low energy ice environments and herder toxicity (ongoing 2014/15). There are major differences between different nations and states regarding the acceptability of different response techniques. Recently published reports review these differences for all the Arctic countries (Arctic Response Technology JIP, 2013/14).

NEBA (Chapter II-4) can provide a valuable tool for objectively assessing relative risks and benefits and, hopefully, lead to better, more informed decision making on the part of responders, regulators, and local stakeholders in approving dispersants and burning as accepted response techniques. Each strategy, including mechanical containment and recovery, has an important role to play in the overall response toolbox. The extent to which one approach is favoured over another in an operational situation depends on a host of factors and variables, including the results of a NEBA.

The following four sections, V-3 through

V-6, discuss the principal response strategies applicable to oil spills in ice-covered marine areas. In many cases, reference is made to research through basin testing, and field trials, and to accidental spills in ice involving vessels, for example the *Godafoss* incident in Norway.

Fortunately, there has never been a significant spill from an oil exploration or produc-

tion facility, or a pipeline in ice. Consequently, opinions and ideas on the combination of strategies that would likely work best on any future incident associated with oil and gas activities in ice are primarily based on lessons learned from the many studies and test programs conducted over the past 45 years.

Chapter V-2 Detection, Delineation, Monitoring and Tracking

- In order to mount an effective response, it is critical to know where spilled oil is at any given time and the condition of that oil (degree of weathering).
- Tracking oil in ice and snow will be challenging. Existing trajectory models are limited in their capability to model oil fate and behaviour in the presence of a range of sea ice conditions. Trajectory uncertainties would be larger than usual in Arctic regions because of limited meteorological and oceanographic data inputs. Updated trajectory forecasts may also be less reliable because of reduced overflight reconnaissance due to poor flying weather with limited visibility.
- A mix of conventional airborne sensors is likely to prove effective with spills in relatively open ice cover (1-4/10) where there is a distinct oil slick covering areas of hectares or more – analogous to open water with some ice present.
- The use of remote sensing to detect spills contained in closely packed ice is still uncertain, requiring all weather, high resolution capabilities that have yet to be fully tested in a field situation.
- The lack of significant waves in the presence of ice complicates the use of marine or satellite radar systems, both of which depend on differences in surface roughness (oil versus no oil) as a means of detection.
- With adverse weather or darkness, obtaining consistently reliable detection and mapping of oiled areas becomes challenging and requires a mix of remote sensors operating in different parts of the electromagnetic spectrum.
- The detection of oil underneath and within the ice remains a challenge. Recent promising developments in this area include the use of ground penetrating radar from above and sonar from beneath the ice.
- Future platforms will likely involve both unmanned aerial systems (UAS) and autonomous underwater vehicles (AUVs).
- There is an extensive ongoing research effort to evaluate the capabilities of a range of surface and subsea sensors to detect oil trapped in ice (ART JIP 2014).
- Sensor performance in brackish ice such as found in the Baltic Sea may benefit from the relatively low brine volume affecting the structural and electrical properties of the ice sheet, for example lower conductivity reducing the attenuation of radar energy.

The first response activity often involves aerial reconnaissance to document the extent of the oiled area and to track the initial oil spreading and drift patterns, as well to identify marine resources at risk. Safety of crew and passengers is always the number one priority before any spill response begins. In this regard, the commitment of surveillance aircraft and heli-

copters to on-going search and rescue (SAR) operations could delay oil spill mapping and aerial observations in the immediate time period following an accident. Such a conflict with limited air resources being multi-tasked happened in two consecutive years on the SINTEF Oil in Ice JIP. This example is described here as an illustration of what could

happen in an actual Arctic spill emergency. In the first year, 2008, the Norwegian patrol aircraft was called out on a real spill from a platform in southern waters, the morning when a remote sensing over flight was scheduled to coincide with the largest experimental spill of the program. In 2009, a Russian freighter grounded on the rocks of Bear Island a few days prior to start of the experiment. The primary vessel assigned to the project, KV *Svalbard*, was detoured to assist with the accident, delaying the start of the experimental program. As a result the Swedish aircrew (also called to assist in overflying the incident) ran out of duty time and had to return to their home base without completing the full remote sensing mission aimed at detecting oil in ice. In future, expanded use of more capable unmanned aerial vehicles (UAVs) could lessen these conflicts when limited aviation resources are available, while reducing personnel risk at the same time.

Finding and mapping oil in ice, even under favourable weather and light conditions, is far from straightforward. For example, there have been a number of situations where an icebreaker or commercial cargo vessel has incurred ice damage sufficient to rupture bunker tanks without the crew being aware of the ongoing fuel loss. One case involved a cargo vessel in the St. Lawrence River where an oiled track was only discovered in the spring when the oil was exposed by ice melting (and was successfully dispersed by applying natural clay fines referred to as OMA). A key element of this type of dispersion process is that the fines are less dense than water so that the resulting oil-fines emulsion remains at the sea surface. In another case, crews on an icebreaker in the Canadian Arctic found a substantial loss in bunkers during a routine check of tank levels after hundreds of kilometres of transit through ice: the spill was never found.

Detection is clearly not a critical issue in the case of a large visible spill around a vessel resulting from a major damage incident, or around a fixed drilling platform. However, continued monitoring and tracking of the oiled ice as it moves away from the original discharge point in a dynamic pack ice environment presents a significant challenge. The vessel and the oil may become quickly

separated by tens of kilometres as they drift at different rates. Over the winter season, the oil could drift hundreds or even thousands of kilometres from the spill source. GPS ice tracking buoys can help track oiled ice in the same manner they have been used for decades to successfully track unoiled ice movements throughout the Arctic Basin. Operational questions center around the ability to deploy a sufficient number of beacons to accurately define the track as the ice fragments and diverges to follow different paths over a period of months following a spill. These beacons could be part of the required OSR inventory for an Arctic exploration well, but are unlikely to be readily at hand in large numbers in the case of a vessel spill.

Other spill scenarios make immediate detection much more difficult: for example, oil flowing out onto the ice surface and then buried under fresh snow and hidden from view, or a submerged vessel leaking small volumes of oil beneath a moving winter ice cover.

a. Sensors and Platforms – Current Capabilities

Detection and mapping of oil in ice requires a mix of sensors operating in different spectral bands, both passive and active. Figure V-2.1 is a montage of platforms and sensors ranging from AUVs and sonar, to dogs, and Synthetic Aperture Radar (SAR) satellites.

Included in the mix is the human observer, perhaps still the most reliable “sensor”, in spite of the limitations of darkness and adverse weather.

Much of the early research on spill detection in ice took place over a ten-year period beginning in the late 1970s, motivated by offshore drilling programs in the Canadian Beaufort Sea. Researchers carried out analytical, bench, and basin tests and field trials using a wide range of sensor types: acoustics, radar, ultraviolet fluorescence, infrared (IR), gamma ray, microwave radiometer, resonance scattering theory, gas sniffers, and ground penetrating radar (GPR) (e.g., Dickins, 2000; Goodman 2008).

In 2004 the US Minerals Management Service (now BSEE) and industry funded out a test basin study at CRREL in New Hampshire,

Table V-2.1 Overview of Remote Sensing Systems for Oil in Ice Detection (Dickins and Andersen, 2009).

Platform	Ice Surface		AUV	Shipborne		Airborne					Satellite
Sensor	Dogs	GPR	Sonar	Marine Radar	FLIR	GPR	Visible	UV	FLIR	SLAR	SAR
OIL ON ICE											
Exposed on cold ice surface	Y	N/A	N/A	N	Y	Y	Y	N	Y	N	N
Exposed on spring melt pools	Y	N/A	N/A	?	Y	N	Y	?	Y	?	N
Buried under snow	Y	Y	N/A	N/A	N	Y	N	N	N	N	N
OIL UNDER ICE											
Smooth fast ice	?	Y	Y	N/A	N/A	Y	N/A	N/A	N/A	N	N
Deformed pack ice	?	?	Y	N/A	N/A	?	N/A	N/A	N/A	N	N
OIL IN ICE											
Discrete encapsulated layer	?	Y	?	N/A	N/A	Y	N/A	N/A	N/A	N	N
Diffuse vertical saturation	?	?	N	N/A	N/A	?	N/A	N/A	N/A	N	N
OIL BETWEEN ICE FLOES											
1 to 3/10 concentration	N/A	N/A	N	Y	Y	N	Y	Y	Y	Y	Y
4 to 6/10 concentration	N	N/A	N	?	Y	N	Y	?	Y	?	?
7 to 9/10 concentration	?	N/A	?	N	Y	N	Y	N	Y	N	N
LEGEND											
Likely	Y										
Possible	?										
Not likely	N										
Not Applicable	N/A										
Blocked by dark/cloud/fog/precip											

Source
DF Dickins Associates (2010)
for SINTEF Oil in Ice JIP

based on information gathered during those experiments and from results of previous trials, not necessarily in the Arctic.

Overall conclusions from this work were that the current generation of airborne systems have a high potential for detecting and mapping large spills in very open ice, but much less potential as the ice concentration increases. Many non-radar sensors are blocked by darkness, cloud, fog, and precipitation, all of which are common over Arctic waters for much of the year.

A quantum leap in all-weather remote sensing capability occurred in the late 1990s with the advent of commercially available, high-resolution SAR satellite systems, which are unaffected by darkness or cloud cover. The latest generation of these satellite sensors can now resolve targets less than a metre across, albeit over relatively small viewing areas of tens of kilometres (e.g., Radarsat 2, ERS-1, TerraSAR-X, COSMO-Skymed). The first generation of SAR satellites monitored and mapped large slicks at sea during the *Nakodka*, *Sea Empress*, and *Prestige* oil spills (Hodgins et al., 1996; Lunel et al., 1997). Although the capabilities of SAR satellites in an Arctic spill response are still not fully understood, their demonstrated ability to detect and map large slicks at sea under moderate wind conditions is expected to apply to well-defined oil slicks spreading among very open to open pack ice where capillary waves can still develop on the surface (Babiker et al., 2010).

The Macondo oil spill provided an opportunity to utilise many of the latest detection technologies to monitor very large slicks in open water. Leifer et al. (2012) summarise how passive and active satellite and airborne marine remote sensing were applied extensively in monitoring the slick area as well as thickness with quad polarisation. It is not clear whether and to what extent these technologies and strategies apply to an oil spill in ice.

There will always be a need for well-trained observers flying in helicopters and fixed-wing aircraft to detect and map oiled areas and to transmit critical information to response crews. For example, spotter aircraft were essential to the success of individual ISB operations during the Macondo response (Allen et al., 2011). Advanced pollution surveillance aircraft with the varying potential to respond to Arctic spills in ice are operated by the USA (untested north of 60°), Norway, Sweden, Finland, Canada, Germany, Estonia and Iceland among others.

Figure V-2.2 shows an example of one of these aircraft the Swedish Dash 8 Q300 equipped with a combination of FLIR, SLAR, UV/IR and SAR sensors.

A key aspect to the future effectiveness of airborne remote sensing systems is the ability to integrate different datasets into a useful real-time or near-real-time product that responders can use with minimal interpretation. There has been considerable progress on multispectral data fusion applied to pollution

Figure V-2.2 Swedish Q300 aircraft representative of the state of the art in open water maritime pollution surveillance (Photo: Swedish Coast Guard).



surveillance aircraft tasked with searching for open water spills, but the knowledge necessary to apply similar common operating picture or fusion algorithms to spills in ice has yet to be developed (Baschek, 2007).

Commercially available ice-strengthened Global Positioning System (GPS) beacons and buoys are commonly used to track ice movements over an entire winter season throughout the polar basin. Tracking the location of oiled ice in a moving ice cover may require deploying large numbers of beacons at regular intervals onto the ice as it moves away from the spill source. This track can then be used to direct airborne and marine response resources to locations most likely to contain oil. Closely spaced GPS beacons can follow the evolving pattern of spill fragmentation and divergence as the pack expands and contracts, for example as observed by following a spill through the winter in Baltic ice (Hirvi et al., 1987). This data is a key component of trajectory modelling, which is discussed in Chapter II-3d.

b. Promising New and Recent Concepts/Developments in Detection

A number of systems tested over the past ten years, including GPR, are capable of detecting oil in and on ice in both airborne and surface operations. Tank and field experiments from 2004-2006 demonstrated that surface-based, commercially available GPR can detect and map the presence of oil films as thin as 1-3 cm underneath one metre or more of solid ice, or trapped as layers within ice (Dickins et al., 2006). In 2008, the same radar suspended beneath a helicopter traveling at speeds up to 20 knots and altitude up to 20 m successfully detected a thin layer of crude oil buried under

hard-packed snow (Bradford et al., 2010). A prototype frequency-modulated continuous wave (FMCW) radar designed to detect oil trapped under/in solid ice from a low-flying helicopter, was developed in 2011. An ongoing test program at CRREL, New Hampshire, plans to compare results from a variety of sensors, including the radar (ART JIP November 2014 to January 2015).

More recently, consideration has been given to the application of nuclear magnetic resonance (NMR) as potential means to detect oil trapped under or in ice in the future, although further testing is needed to evaluate the practicality and effectiveness of an operational system (Nedwed et al., 2008). Ongoing (late 2014) research involves testing a full-scale NMR prototype over an outdoor frozen test pond in New Hampshire. There are several drawback the future operational application of this technology such as the need to fly a large circular antenna (approximately 6 m diameter), and the need to remain stationary for short periods at discrete sampling points to gather sufficient data for processing.

Infrared (IR) systems (alone or in conjunction with high-speed marine radar and low-light-level video) can also be used from the surface, low-flying helicopters, aircraft (tracking high resolution forward-looking IR), or vessels. In 2009 SINTEF JIP tests, a basic uncooled hand-held IR sensor was able to distinguish between oil, ice-free water and snow, and clean ice floes during daytime (Dickins et al., 2010).

Also as part of the SINTEF JIP, trained dogs on the ice tracked and located small oil spills buried under snow from a distance of 5 km, and also determined the approximate dimensions of a larger oil spill (Brandvik and Buvik, 2009).

X-band marine radar (MIROS and Rutter systems) successfully detected slicks at sea in large-scale trials. These same systems may be able to detect oil slicks in open drift ice but have not been tested. (Dickins and Andersen, 2009). Integrated systems such as the Aptomar SECurus that combine high-resolution forward-looking infra-red and low-light cameras are also deployed on emergency response vessels in Norway. Some of these vessels operate

in Arctic waters, for example, the KV *Svalbard*.

UAVs and autonomous underwater vehicles (AUVs) already have the capability of carrying useful sensor packages over long distances (albeit at slow speed) for Arctic oil spill surveillance (Wadhams et al., 2006). For close-in work where the general location of a spill under ice is already roughly known, ROVs operating on a long umbilical could map the extent of contamination and define the spill boundaries. Both single- and multi-beam sonar sensors successfully detected and mapped oiled boundaries and thicknesses under ice in a recent basin test at the U.S. Army CRREL facility (Wilkinson et al., in preparation). A September 2013 exercise aboard the USCG *Healey* field-tested UAVs, AUVs, and Arctic skimmers for response capabilities (USCG, 2013). Further testing of different UAV sensors under oil spilled in ice took place in Germany at the HSVA facility in Hamburg in late 2013 sponsored by the European Union (Wilkinson et al., 2013).

The overall goal is to develop operational systems that can reliably detect oil spilled on, among and under ice in a wide range of conditions. This remains a major challenge and is the subject of ongoing research by a number of different groups such as the Arctic Response Technology JIP. The JIP is currently (2014) undertaking the first controlled comparison test of different airborne and subsurface sensors in detecting oil beneath, trapped within and on top of sea ice through an entire ice cycle from freeze-up to melt (Dickins, 2014).

c. Trajectory Analysis and Oil Transport Prediction/Modelling

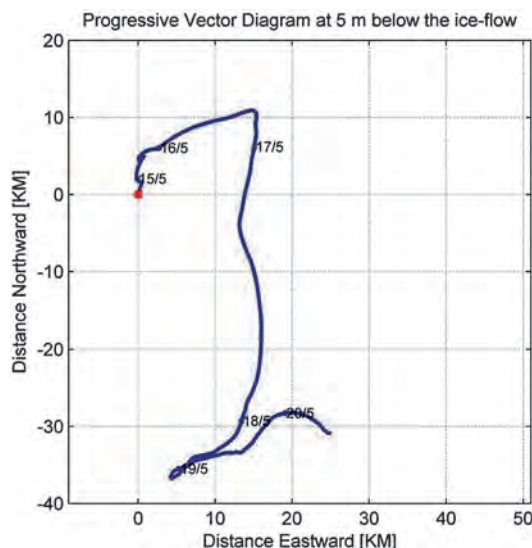
Oil trapped within pack ice over 6/10 concentration tends to move with the ice at 3-5% of the wind speed with a turning moment up to 30 degrees to the right in the Northern Hemisphere, due to the Coriolis effect. Oil in more open drift ice can move at different rates from the ice: for example, thick, rough floes with large sails and keels experience different driving forces from currents and winds than a slick on the surface. There is considerable variability with more open drift ice moving faster relative to the wind than a more compact ice cover (more freedom to move). In more than 6/10 ice concentration, the floes tend to be in contact at some point around their perimeter making it fairly difficult for oil to move at substantially different rates than the surrounding ice cover. In lower ice concentrations, oil can easily spread through the gaps between floes resulting in different drift speeds depending greatly on the ice freeboard and roughness (sail effects) as well as the potential for thicker ice to respond to currents at depth different from the wind force.

Figure V-2.3, based on data from actual experimental spills in ice, shows how oiled ice can move large distances, tens of kilometres, in a short period of time during storm events. In other areas, such as in offshore Sakhalin Island, similar displacements routinely occur in a single day in response to strong tidal currents.

Mark Reed of SINTEF discusses the current state of knowledge surrounding oil spill trajectory modelling in ice (NRC, 2014) and this material provides the basis for the following discussion. Several reviews of oil spill modelling technology are available (Huang, 1983; Spaulding, 1988; ASCE, 1996; Reed et

- The movement of an oil slick on the sea surface is driven by winds and surface currents acting either on the slick directly, or in the case of a spill in ice covered waters, acting on the ice features as well as the surface waters between the floes.
- The mechanisms governing spill movement are complex, but experience shows that oil drift on water can be predicted with reasonable accuracy from a simple vector calculation of wind and surface current direction, based on a multiplier of the wind speed and 100% of the current velocity.
- Current efforts to improve the predictive capabilities of oil spill trajectory models in the presence of ice are focused on improvements to the existing sea ice models, with much better spatial resolution, and a more realistic treatment of under ice roughness, individual ice features, and dynamics.

Figure V-2.3 Actual oil in ice drift track from the 2009 SINTEF oil in ice JIP experiment in the Norwegian Barents Sea. Note the 35 km southerly displacement on May 18 during a period of sustained wind speeds over 15 m/s (30 kt). The drift rate closely matched the general rule of thumb in terms of 3% of wind speed (Source: Sørstrøm *et al.*, 2010).



al, 1999; Yapa *et al.*, 2006; Drozdowski *et al.*, 2011). A key problem lies in the limited ability to model the behaviour of the ice itself at the necessary spatial scales, which are in the order of metres. A real-time forecasting attempt reported by Reed and Aamo (1994) and model development and hind-casting work by Johansen and Skognes (1995) exemplify the problems encountered when oil-ice interaction models are put into active use in the field. Ice coverage is a dynamic variable, and can change from 10 to 99% overnight, with significant consequences for oil weathering and transport.

Gjøsteen *et al.* (2003) produced a model for spreading of oil in irregularly shaped simulated ice fields. Some Russian researchers are also active in this area (e.g., Ovsienko *et al.*, 1999). Both Gjøsteen and Ovsienko have developed spreading models that account for spreading of oil among ice floes. Incorporation into numerical models of these advances, as well as increased understanding of oil weathering processes in the presence of sea ice, have been hindered by the interdisciplinary nature of the problem. Significant advances in oil-ice interaction modelling require that knowledge of oil behaviour and fates, ice cover, and hydrodynamic models, be integrated: to date this type of integration is not available.

Achieving higher spatial resolution using existing classical sea ice models is not sufficient, as robust oil spill models will need more detailed representations of sea ice (e.g., ice floe sizes, ice porosity, ice drift, ridging and growth rates, under-ice roughness). Advancement in

this direction is needed for both sea ice and oil spill models, although neither is likely to reliably perform at this level of detail in the near future.

d. Promising New Developments in Trajectory Modelling

Promising advances in sea ice modelling in the past decade include detailed models of brine-channel formation and drainage by Petrich *et al.* (2006; 2013). This approach allows for incorporation of oil into brine channels as well as bulk freezing into ice (Faksness *et al.*, 2008; 2011). Hopkins (1996; 2003) has developed a discrete element approach to modelling sea ice that allows for variably sized ice floes. These two advances together permit a parameterisation of oil-ice interactions at a conceptual resolution that is significantly closer to reality than was previously possible.

Wilkinson *et al.* (2007) have demonstrated the possibility of modelling the flow of oil under sea ice based on the topography of the under-ice surface mapped by AUV. Future ice models will need to produce an estimate of under-ice roughness if the spreading process is to be adequately represented.

Other advances in oil spill modelling are occurring, although they are driven mostly by the Macondo response rather than issues associated with the Arctic. There is a strong focus on underwater near-field plume modelling, including the effectiveness of dispersant injection at the wellhead. This work could have implications in the future for modelling similar plume behaviour for Arctic subsea blowouts.

The Arctic Oil Spill Response Technology JIP recently (2014) initiated a research effort to improve oil spill trajectory modelling capability within the Arctic, with plans to develop new sea ice models related to ice dynamics (Mullin, 2012).

e. Sampling and Monitoring for oil detection and characterisation

- A sample collection and monitoring plan may be desirable for a variety of reasons, but primarily to identify real or potential risks to responders, the public, and to the environment.
- Samples are collected and analysed to monitor the changes in physical and chemical properties through time and to forecast the behaviour, persistence, and fate of the oil.
- Sampling and monitoring of spills in ice and snow are particularly important because most available data is from prior studies or spills in warmer, open water environments where the oil behaviour and fate are fundamentally different.

Samples are collected for a variety of reasons but primarily to provide information and data for:

- Detection
- Fingerprinting for source identification
- Characterisation for safety planning
- Measuring the concentrations in water or sediments
- Characterisation for risk analyses
- Monitoring changes in the physical and chemical properties of the oil

Fingerprinting for identification purposes (Stout and Wang, 2007) may not be necessary if the source is obvious but would be important in the event of a “mystery spill”. In most cases, oil characterisation would also be conducted to define potential safety risks for responders (IPIECA/OGP, 2012a). Samples would be collected and analysed to address key working environment safety issues that include:

- Potential risk of explosion or fire
- Levels of volatile organic compounds (VOCs)
- Potential for mitigation measures including Personal Protective Equipment (PPE)
- Risks to responders or the public
- Safety or exclusion zones
- Monitoring for flammable or toxic fumes

Sampling and monitoring may not be necessary on all spills, for example, if the volume is small and no environmental risks are involved, as may be case for oil spill on stable ice with ample opportunities for vapours to disperse downwind. Generally, in terms of oil behaviour and fate, it is important to recognise that data from prior studies or spills in warmer environments may not be applicable as spills in ice and snow are fundamentally different from spills in open water or on land. For example, cold air and water temperatures slow weathering processes and promote the persistence of thicker oil films in lower sea states. Monitoring would also be important for oil trapped in snow on ice or on a shoreline to show rates of change as a result of evaporation, which is the single most important weathering process (Buist 2000).

Typically an oil sampling and monitoring plan will be developed early in a response and may be part of a broader programme that could include oiling assessment (Part VI.1) and ecological surveys (Owens et al., 2007). In all cases, the plan should clearly identify the objectives (ITOPF, 2014) and the sampling programme should follow agreed standard collection, handling, storing, and analytical protocols.

The objectives of a sample and monitoring plan could include:

- Delineation of the area(s) affected by the spill,
- Identification of background and incident-specific contributions of oil,
- Description of any variations in oil character, concentration, and mode of occurrence in space and time,
- Evaluation of the variability of oil concentrations in water samples or oil penetration depth in ice, snow or sediments,
- Generation of data to help forecast the persistence and fate of the oil, and
- Generation of data of potential use to understand oiling effects on resource use.

Chapter V-3 Mechanical Containment and Recovery

- Potter et al. (2012) define “containment and recovery” as actions taken to remove oil from the surface of water by containing the oil in a boom and/or recovering the oil with a skimming or direct suction device or sorbent material.
- After removal, the recovered mix of oil and water and contaminated materials need to be stored offshore until they can be transferred to an approved disposal or recycling facility.
- Mechanical containment and recovery is often preferred over other oil spill countermeasures because it is viewed as directly removing oil from the marine environment.
- The recent experience with using mechanical recovery on an unprecedented scale in the Macondo response highlights a key drawback of mechanical containment and recovery systems when confronted by a large, rapidly spreading oil slick: namely, the encounter rate is insufficient to allow the skimmers to achieve a significant percentage of their theoretical recovery capacity (Allen, 1999). This problem is amplified greatly by the presence of any significant ice cover.
- Although not necessarily the most effective strategy for dealing with very large Tier 3 incidents in remote areas, mechanical recovery has an important role to play in responding to smaller spills, especially in areas where there is sufficient infrastructure and marine resources to support the need for lightering, storage, and disposal.

Conventional booms and skimmers become increasingly ineffective as ice concentrations increase much beyond 1/10 (10% or more ice coverage). Limited effectiveness is still possible in very open drift ice (1/10-3/10 ice concentration) and in isolated polynyas within closer pack ice. However, even the presence of very small fractions of ice interferes with boom operation and quickly reduces flow to the skimmer head. The end result is that the realised recovery rates with ice present tend to fall far short of the skimmer’s theoretical capacity (Bronson et al., 2002; Potter et al., 2012; Schmidt et al. 2014).

Sea state is another important consideration for any recovery method that relies on containment before collection or removal. Oil is often entrained beneath or splashed over booms in short-period wind-waves exceeding 3-5 feet (1-1.5 m), although booms can accommodate higher significant wave heights in a long-period ocean swell. The issue of boom limitations in high waves also affects the practicality of using *in-situ* burning in rough sea conditions. Increasing wave heights also make equipment deployment/retrieval difficult, reduce the effectiveness of skimmers, and may result in unsafe working conditions. Although any significant ice cover effectively dampens the wave energy, it is still possible to encounter severe sea states near the ice edge in a mar-

ginal ice zone (transition from pack ice to the open sea as found for example in the Bering and Barents Seas) with widely dispersed ice floes.

There are significant problems in relying principally on mechanical containment and recovery to deal with large offshore spills in a remote area. Even under favourable sea conditions and with almost unlimited marine resources and coastal infrastructure, mechanical recovery in the Macondo spill only accounted for an estimated 2-4% of the oil volume discharged (Federal Interagency Solutions Group, 2010).

The length of boom, which can be deployed and maintained under freezing conditions, even for a short period, depends on the severity of the ice conditions. Any limited containment of oil, which may be possible in very open drift ice requires rugged, high-strength booms to withstand contact with the ice. Field trials in 2008 and 2009 in Norway demonstrated that, although heavy fire boom could collect and contain significant amounts of ice distributed as small floes (2-5 m diameter) at slow speeds without failure, the only practical means of removing the oil in ice after collection in this situation was through burning (FigureV-5.2).

Intensive and costly international efforts to develop dedicated mechanical systems for

operations in naturally broken ice have not progressed beyond the small-scale prototype stage, for example the MORICE project (Mullin et al., 2003). The problems and impracticality of scaling up such systems to achieve useful oil encounter and recovery rates in an Arctic environment have stalled further developments of systems dependent on ice cleaning or processing to deal with very large spills.

The fundamental limitations associated with maintaining and operating booms and skimmers in ice are further complicated in polar areas by the lack of coastal infrastructure, and approved on-land storage sites. Although Arctic infrastructure may improve in the future with increasing oil and gas production, it is unlikely ever to approach the levels of support available in more temperate areas. During the 2011 Arctic Offshore Drilling Review commissioned by the Canadian National Energy Board, all three industry proponents proposed relying on other strategies such as burning and dispersants as the basis for their oil spill contingency plans supporting future exploration wells in the Beaufort Sea (e.g. Chevron 2011). The recent National Research Council Committee on Responding to Spills in the U.S. Arctic Marine Environment concluded that “very large oil spills require a response approach that does not solely depend

on mechanical recovery” (NRC 2014).

Mechanical recovery does have an important role to play in dealing with the more likely occurrence of smaller spills in ice and in areas where other options are not acceptable. It is the preferred response strategy in the Baltic Sea for a number of reasons, such as the inappropriateness of dispersant use in the relatively shallow, poorly mixed, and biologically productive waters. As a result, manufacturers in Denmark, Norway, Sweden and Finland have become world leaders in designing and manufacturing spill containment and recovery systems for harsh winter environments.

Spills in winter shipping lanes in the Baltic Sea are routinely recovered with brush/bucket skimmers (Lampela et al., 2007; Bergström, 2012.) (Figures V-3.1 and V-3.2). In 2011, Norwegian responders recovered 50% of 939 bbl (112 cubic metres) of heavy fuel oil spilled into freezing waters of Oslo fjord from the *Godafoss* (Bergström, 2012). This latter incident is discussed in more detail below as the most recent example of a successful mechanical recovery operation in ice.

A number of Baltic and Scandinavian countries operate a fleet of specialised vessels designed for operations in ice. Notable are a number of vessels employed in Finland that utilise specialised oiled ice separation and



Figure V-3.1 Hylje Finnish oil spill response vessel using an over-the-side brush bucket on a hydraulic arm (see close-up below) to recover oily bilge pumped illegally into the winter shipping lane in the Baltic in March 2003 (Source: Finnish Environment Institute, SYKE).



Figure V-3.2 Close-up of the brush bucket skimmer operating in ice (Source: Lamor Newsreel).

cleaning systems, internal as well as over-the-side skimmers and integral brush skimmers fitted to the stern, as in the latest oil spill recovery vessel *Louhi*. These systems are tailored to the Baltic ice environment and the small ice piece sizes commonly found in winter shipping channels (Ryttonen et al., 2003; Wilkman et al., 2014)(Figure V-3.3). In general, these systems have limited applicability to Arctic spills with much thicker ice and larger floe sizes. An exception is the over-the-side brush/bucket skimmer that could potentially recover small patches of oil between Arctic ice floes.

The latest multi-purpose oil spill response vessel designed to respond to spills in ice, the *Louhi* entered full operational service in Finland in the summer of 2011 and, along with

other systems, has the capability to deploy a stern-mounted rotating brush skimmer across the full beam of the vessel in an effort to increase the encounter rate while proceeding astern into a slick (Figure V-3.4). Sweden also has specialised oil recovery vessels with ice capability and Russia recently (April 2014) took delivery of a new oblique icebreaker that uses an asymmetric hull form to break much wider tracks (up to 50 m) through the ice than conventional designs. Oil spill response is one of the roles assigned to this new vessel but the built-in brush skimmer system is designed mostly for open water use (<http://arctech.fi/fi/wp-content/uploads/Baltika-ENG.pdf>).

In accord with the Copenhagen agreement, Baltic nations conduct annual exercises with vessels from different countries participating in winter drills. For example, *Kalajoki 2013 Oil in Ice* took place in the Bay of Bothnia and involved two vessels from Finland (*Louhi* and *Seili*) and Sweden (KBV 181 *Gotland*)(Figure V-3.5). The Finnish vessels utilised a combination of brush systems at the stern and an oil recovery bucket from a crane. The Swedish vessel uses an endless brush rope mop system for recovery in ice. Source: http://portal.helcom.fi:81/Archive/Shared%20Documents/RESPONSE%2017-2013_Presentation-2.pdf.

A large number of tests in the USA, Can-



Figure V-3.3 Finnish OSRV *Linja* with the LOIS vibrating grid oiled ice cleaners mounted on either side in collecting mode. This view clearly shows the limited swath width possible with these systems (Photo: Lamor Newsreel, 2011).



Figure V-3.4 Louhi, the latest generation of multi-purpose oil spill recovery vessels for the Baltic (Photo Source: Wikipedia).

ada, and Norway have focused on testing different skimmer designs in a wide range of pack ice conditions (Singsaas et al. 2010). The SINTEF Oil in Ice JIP tested a number of new Arctic skimmer prototypes in tanks and offshore field trials in 2008 and 2009. Several of these prototypes are now available commercially through manufacturers in Finland and Denmark (Sorstrom et al., 2010), several examples of which are shown in Figure V-3.6.

Advances with skimmers include improved oil and ice processing, the ability to handle larger volumes of cold viscous oils and oil/ice mixtures with low water uptake, and the heating/enclosing of critical components to prevent freezing. Various viscous oil pumping systems and techniques have also been developed to facilitate efficient transfer of cold and viscous mixtures of oil, water and small ice pieces (Potter et al., 2007). An additional

advance utilises skimmers capable of independent propulsion to allow them to access oil up leads and between openings in the ice over limited distances dictated by the need for a hydraulic umbilical, as in the photo at bottom right in Figure V-3.6.

Mechanical recovery of oil spilled under fast ice is possible through cutting, trenching, and drilling while using the ice cover as the working platform (ACS, 2013). Figure V-3.7 shows an example of various techniques suitable stable ice nearshore. Depending on location, oil recovered in this manner can be transported to shore over smooth ice or on ice roads for disposal and/or reinjection in on-shore wells. These proven mechanical response strategies are most applicable to nearshore locations such as off Prudhoe Bay, where stable fast ice extends tens of kilometres offshore and persists for over eight months of the year.



Figure V-3.5 Gotland, Swedish multi-purpose oil spill recovery vessel operating in ice (Photo Source: MarineTraffic.com, Photographer: Arui-Jukka Perkiomaki).

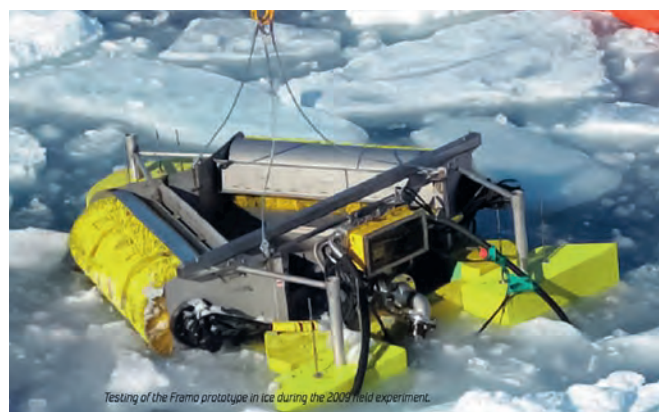


Figure V-3.6 Different skimmers from manufacturers in Denmark and Finland, evaluated in tank and field tests during the SINTEF Oil in Ice JIP (Sorstrom et al. 2010).

Mechanical recovery of oil trapped under drifting ice floes in a pack ice environment is a much more challenging case and at present there are no proven technologies or techniques for dealing with such a scenario involving medium to large (Tier 2 or 3) spills. As discussed in Chapter IV-1d, oil spilled under ice is likely to be contained in a relatively localised area by natural undulations in the ice undersurface (reflecting different growth rates affected by varying surface layers of snow).

Under winter conditions when the ice is still actively growing, the under-ice pockets and films of oil quickly become encapsulated between the original ice sheet above, and new ice growing beneath, the oil. In this state, there is no practical way to accurately locate the oil using existing technology (new sensors are being tested and under development but not yet operational) and there is no practical way of safely recovering the oil to the surface. It is not safe to deploy recovery crews on drift-

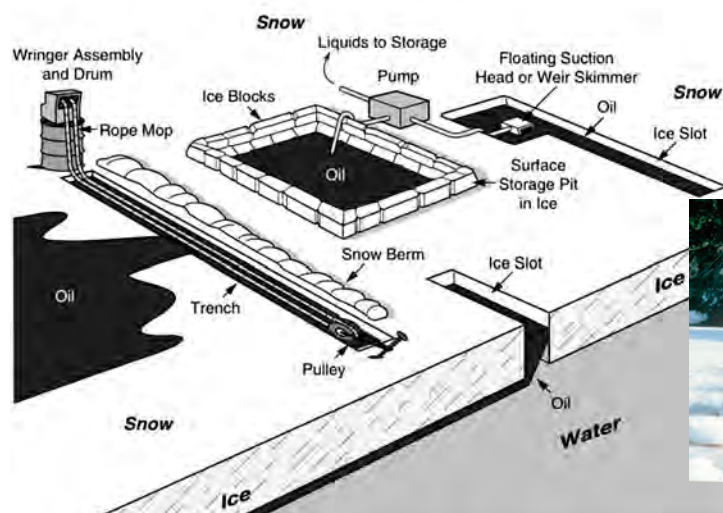


Figure V-3.7 Example of mechanical recovery strategies developed for use on a stable ice cover near shore (Source: Alaska Clean Seas).



ing ice offshore and drilling into isolated oil pools is extremely ineffective in terms of recovery. Lateral oil flow under the ice has been shown to drain only the localised ice area for a few metres at most around the drill hole (Norcor, 1975; Dickins and Buist, 1981). The concept has been put forward by a number of companies to utilise a remotely operated vehicle (ROV) to vacuum oil from under an ice flow but this technique would have serious limitations in terms of the practical length of umbilical and ability to access any significant volumes of oil in the interior of a large floe.

At the end of winter, when the ice has almost stopped growing, the oil would likely remain exposed in a relatively fresh state under the ice until the sheet becomes porous enough to permit the oil to migrate to the surface. Once this happens, the oil becomes visible and potentially accessible. The problem in terms of mechanical recovery is that there is no practical and effective way to recover significant volumes of oil spread on the surface of drifting, melting ice with existing skimming systems. Small volumes could be potentially recovered by using an over-the side brush bucket skimmer as depicted in FigureV-3.1, but this type of operation could not deal with large volumes of oil spread over large area of ice such as would result from a blowout flowing for any extended time period with pack ice moving past the discharge site. A potentially much more effective strategy for dealing with this scenario is to ignite the oil from air when it surfaces in the spring as discussed in Chapter V-5.

The 2011 *Godafoss* incident is introduced in Annex E under the discussion of scenarios and is described here in more detail as the most recent example of lessons learned responding to a vessel spill under freezing conditions. This experience is valuable as it reveals the challenges faced by the responders even with the benefits of considerable infrastructure in the region: which is far more extensive than would be available if a similar accident occurred in most areas of the Arctic.

A considerable portion of the spilled oil was recovered in this case, demonstrating that in spite of the known drawbacks of mechanical recovery in dealing with very large spills, this strategy can work effectively in recovering

oil from small to medium sized spills, even with freezing conditions. The following text from ITOPF (*Ocean Orbit*) details the *Godafoss* spill and the response operation:

"The incident occurred in the Hvaler–Fredrikstad archipelago in a National Marine Park in southern Norway, approximately 10 km from the Swedish border, February 2011. At least two bunker tanks were breached and current estimates suggest approximately 939 bbl (112 cubic metres) of oil (IFO 380) was released into the sea with young ice surrounding the vessel (FigureE.4 in Annex).

Immediately after the grounding, the Norwegian Coastal Administration (NCA) initiated and coordinated aerial surveillance operations in order to monitor the trajectory of the spilled oil and to direct the at-sea recovery operations, which were undertaken in cooperation with the Swedish Coastguard. The presence of large quantities of sea ice, coupled with temperatures of around -20°C, posed a challenge to ordinary spill response strategies and techniques. In some areas oil was either stranded under ice and snow or incorporated within the ice as it formed, causing difficulties for both detection and recovery.

Different recovery methods were employed which varied in their effectiveness in the ice conditions. Booms needed to be sufficiently durable to withstand the extra force created by the contained ice, which could cause them to tear or become temporarily submerged. Most skimmers operated at a significantly reduced efficiency, due to both the high viscosity of the oil and the presence of drifting sea ice within the slick.

Some of the more effective techniques included a combination of brush belt skimmers assisted by steam heating jets, which enhanced the separation of oil from ice. Oil recovery was also achieved using response vessels equipped with sweeping arms to contain the oil, while mechanical grabs were used to transfer the viscous, weathered oil and ice into containers placed on the vessels' decks.

The incident highlighted a number of areas that would benefit from improved technical solutions, such as minimising the quantity of ice recovered with the oil and increasing the effectiveness of pumping highly viscous oil at low temperatures.”

The Norwegian Coastal Administration (NCA) provides additional details on this incident for lessons learned as:

“Due to cold weather and high pressure there was almost no wind during the first days of the oil recovery operation. Currents created long narrow stripes of ice and oil. Night capacity by Radar Infra-red light sensors and AIS drifters made it possible to operate around the clock for 3 days, and this was a major factor for the good results of the oil recovery operation (more than 50 % recovered). A challenging factor was that the water absorbed by the heavy fuel froze in the very cold conditions (sea temperature – 2°C). The behavior of the oil when stranded was very different with frozen water and without (when temperature again raised).” Source: Norwegian Coastal Administration. Additional discussion is also provided in an Interspill presentation by Bergstrøm, R. 2012.

Recent Developments in Mechanical Recovery

Future improvements in conventional mechanical recovery systems are likely to be incremental rather than transformative, for example, in the areas of cold temperature operability (Sørstrøm et al., 2010). The fundamental constraint of limited encounter rate is exacerbated by the presence of ice and is

not easily overcome with existing or proposed systems.

The Bureau of Safety and Environmental Enforcement (BSEE) sponsors an “ice month” at the Ohmsett test facility. Sea ice is grown in a tank at the US Army CRREL facility in New Hampshire and transported in refrigerated trucks to New Jersey. A project at the most recent ice month in the winter of 2014 examined the effects of ice on skimmer performance and provided a new data set, demonstrating how rapidly the oil throughput degraded with increasing concentration of small ice pieces (Schmidt et al. 2014).

Although not generally considered in the category of mechanical recovery, the recent advances in well-capping and possible cap and flow systems can be viewed as a crucial future component of mechanical recovery. They may provide the most effective mechanical means of quickly stopping oil discharge from a sub-sea blowout and minimising environmental damage.

Specialised skimmer systems and vessel-mounted ice cleaners such as the Finnish LOIS system (FigureV-3.3) have an important role to play in dealing with small to medium spills in relatively contained areas such as harbours or the Baltic where vessel spills are most commonly contained within shipping channels with small floe sizes. Recent experience in Norway with the *Godafoss* incident demonstrated that it is possible to achieve a very credible recovery effectiveness with booms and skimmers, even with forming ice and extremely cold temperatures. For large catastrophic spills from tankers or oil drilling facilities in remote areas, reliance on mechanical recovery as the primary strategy is likely to result in a low overall recovery percentage.

Chapter V-4 Dispersion and Oil Mineral Aggregates (OMA)

- Dispersants are designed to enhance natural dispersion by reducing the surface tension at the oil/water interface, making it easier for waves to create small oil droplets (generally less than 100 microns) that are rapidly diluted in the water column, such that natural levels of nutrients can sustain microbial degradation.
- When used appropriately, dispersants can be an effective oil spill response strategy. They are capable of quickly removing significant quantities of oil from the sea surface by transferring it into the water column where it is broken down by natural processes (ITOPF).
- Significant environmental and economic benefits can be achieved, particularly when other at-sea response techniques are limited by weather conditions or the availability of resources. However, as with other response techniques, dispersants also have their limitations and account must be taken of the characteristics of the oil being treated, sea and weather conditions and environmental sensitivities (ITOPF).
- Rapid dilution down drift of the dispersant application can result in oil concentrations below toxicity threshold limits within very short distances.
- Each application needs to consider the specific conditions such as water depth, currents, salinity and temperature profiles and species at risk before making a decision to use dispersants. There is no hard and fast rule in terms of permissible water depth to safely use dispersants – it depends on the particular situation, including consideration of how species could continue to be impacted seriously by oil on the surface or coastlines if dispersants are not used offshore.
- Over the past decade, a series of tank and basin tests and field experiments have proven that oil can be dispersed successfully in cold ice covered waters.
- In recent studies in the laboratory at Point Barrow, Alaska, indigenous Arctic microorganisms effectively degraded both fresh and weathered oil. Most importantly, Arctic species and their counterparts in southern waters exhibited similar tolerance to dispersed oil, and the use of dispersant was not observed to increase the toxicity of the oil (Gardiner et al, 2013).
- The significant contribution of subsea injection in the Macondo response in reducing environmental impacts both offshore and on the shorelines provides a new, potentially highly effective response strategy for dealing with future worst-case discharges from Arctic wells. More work needs to be done to assess the short and long-term environmental implications of this technique and to understand all of the physical and biological processes associated with the use of subsea injection in the presence of an ice cover.
- The potential to negatively impact local fisheries needs careful consideration in making any decision to use dispersants in areas such as Greenland, Barents Sea, the Bering Sea.
- Although widely used as the primary means of combatting open water spills by countries such as the UK, the application of dispersants in an Arctic environment is still highly controversial.
- The application of dispersant directly to the oil and not on adjacent unoled ice floes needs to be addressed before any use.
- NEBA provides a means of assessing the probability and potential extent of impacts ahead of an actual incident and represents a valuable tool in assessing the environmental acceptability of using dispersants in a given scenario.

Following a spill, a certain percentage of the oil disperses naturally into the water column. The extent to which this occurs depends on the type of oil spilled, ambient temperature, and the mixing energy and/or release conditions.

Natural dispersion takes place when the mixing energy provided by waves and wind is sufficient to overcome surface tension at the oil/water interface, breaking the oil slick into droplets of variable sizes. Generally, larger oil droplets rapidly resurface and then coalesce to form an oil slick, while smaller droplets will remain suspended in the water column to be

diluted by turbulence and subsurface currents and will eventually biodegrade.

In most spills, there is insufficient natural mixing energy to disperse a high percentage of the oil without adding dispersants. Dispersants are designed to enhance natural dispersion by reducing the surface tension at the oil/water interface, making it easier for waves to create small oil droplets (generally less than 100 microns) that remain in suspension for long periods. In deep enough water, the suspended oil is rapidly diluted in the water column to below toxicity thresholds of concern.

Dispersants can be applied from the air,



Figure V-4.1 C-130 Hercules from the Air Force Reserve Command's 910th Airlift Wing Drops Dispersant as Part of the Macondo Response Effort (Source USAF).

vessels, or injected directly at the discharge source (for example in the case of subsea blowout). There are limitations to the surface application of dispersants, as vessels can cover only a limited amount of slick in a given time. On the other hand aircraft provide high coverage rates but cannot always optimise the dose rate to the slick thickness. Figure V-4.1 shows a C-130 applying dispersant aerially during the Macondo response effort. There are practical constants governing large scale airborne dispersant application in remote areas. These include: the need for daylight and good weather (visibility and ceiling), and the availability of a large enough dispersant stockpile to sustain an intensive operation.

Dispersants are only effective on some oil types and are unlikely to be effective on more viscous oils, e.g. IFO, HFO. They are most applicable to relatively fresh light to medium crude oil spills where the oil has not had a chance to form stable emulsions.

A major issue with the use of dispersants to combat a large accidental spill in remote areas is access to convenient dispersant stockpiles. Some areas, such as Alaska, have significant volumes on hand but in many Arctic areas dispersants would need to be mobilised and flown in. This is not an easy undertaking, given the limited number of large airstrips capable of handling freight aircraft and offering reliable instrument approaches. In the case of a drilling accident where dispersants are part of the approved oil discharge contingency plan, arrangements to access and apply dispersants in a short space of time would need to

be in place before the drilling approval may be granted by government agencies. In the case of a major vessel incident in a remote area, it would be much more challenging to initiate a full-scale offshore, aerial dispersant application in time to make a difference.

There continues to be considerable debate over the effectiveness of dispersants on crude oil degradation at low seawater temperatures. The main concern is that as the temperature decreases, chemical processes slow down and oil viscosity increases, making it more difficult to disperse.

Over the past two decades, a series of tank and basin tests and field experiments have proven that oil can be dispersed successfully in cold ice covered waters. (Brown and Goodman, 1996; Spring et al., 2006; Nedwed et al., 2007; Mullin et al., 2008; Owens and Belore, 2004). Research shows that dispersants are effective on unemulsified oil at freezing temperatures as long as viscosity does not increase significantly. Experiments to test the effectiveness of eight dispersants on South Louisiana crude oil (which is analogous to that released during the Macondo spill) at 5 and 25°C, revealed that temperature was less critical than expected (Venosa and Holder, 2013).

To overcome the viscosity limits of conventional dispersants in cold environments, recent research has focused on higher viscosity dispersant products that increase contact time with the spilled oil (Nedwed et al., 2011) as well as products with higher concentrations of active ingredients. Wave-basin tests indicate that these improved dispersants might be used to treat conventional oils with dispersant-to-oil ratios as low as 1:100 (compared to the currently recommended 1:20) and to disperse high viscosity oils like heavy crude and fuel oils (Nedwed, 2010).

The SINTEF Oil in Ice JIP evaluated the effectiveness of dispersants under Arctic conditions, including under cold air and water temperatures, in the presence of ice, and in brackish water from melting ice and river outflows (Daling et al., 2010). As part of this project, a new controllable applicator arm was developed to deliver dispersant more effectively to isolated oil pockets in the ice (Figure V-4.2).

The presence of ice can also increase the

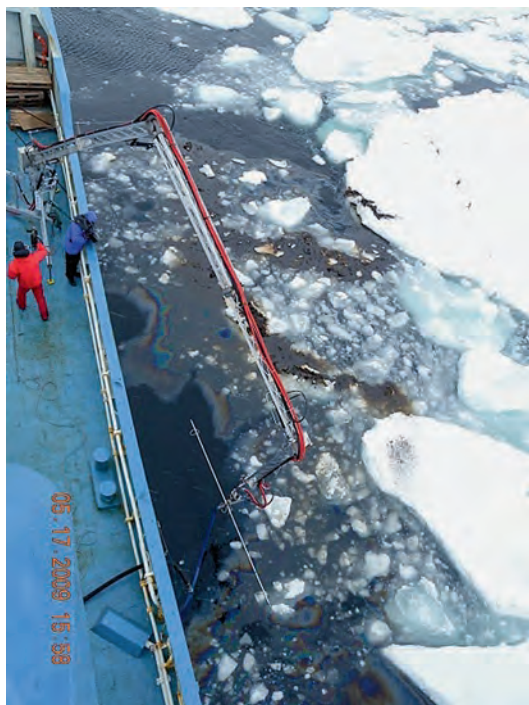


Figure V-4.2 View of the specialised dispersant application arm developed and tested in the SINTEF Oil in Ice JIP in 2009 in the Norwegian Barents Sea with the aim to improve the targeting and delivery of dispersant to isolated oil patches among ice floes (Photo: D. Dickens).

length of time that a dispersant is effective, by slowing the rate of oil weathering and emulsification (Figure IV-1.2). Wind-wave action that facilitates dispersion in open water is generally dampened by the presence of ice. However, the mixing energy created by the interaction of individual ice floes in response to winds and currents can result in more effective dispersion than would otherwise be possible without the presence of ice under similar wind conditions. This process was documented during experiments at Ohmsett (Owens and Belore, 2004)(Figure V-4.3).

Mechanical mixing may be needed to overcome the lack of turbulent mixing energy in scenarios involving significant ice cover: for example, vessel propellers or thrusters can provide artificial mixing energy while adding chemical dispersants to oil, an effect documented in tank tests and at sea (Nedwed et al., 2007; Daling et al., 2010). Dispersion of oil at low temperatures in the presence of ice can also be enhanced with the addition of mineral fines under turbulent mixing conditions provided by propeller wash (NRC 2014).

A successful dispersion of oil in simulated broken ice in the Ohmsett test tank in 2004

(Figure V-4.3), was one of the first meso-scale tests proving that dispersants have a role to play in dealing with a spill in ice. The insert picture shows the Finish icebreaker *Fennica* demonstrating her ability to add large amounts of mixing energy laterally from the rotating azimuth drives. This mechanically induced mixing energy can extend the use of dispersants into higher ice concentrations where the natural wave-induced energy is relatively minimal to non-existent.

Concerns are frequently raised about the potential toxicity of dispersants in current use. Key factors determining toxicity for a given species are concentration and length of exposure time. Dispersants themselves are rapidly diluted in the ocean to less than 1 mg/L (1 ppm) within an hour, below defined toxicity threshold limits (National Research Council, 1989; Lee et al., 2013). In US waters, only dispersants that meet US Environmental Protection Agency effectiveness criteria and that have data from specific toxicity tests may be listed for use during an oil spill response. Other national bodies, such as the MCA in the United Kingdom, impose their own standards.



Figure V-4.3 View of successful dispersion occurring with oil in simulated broken ice (Sources: Owens and Belore (2004), Aker Arctic).



There is also considerable debate on the rate and extent of oil biodegradation in arctic waters. Recent studies in a laboratory at Point Barrow, Alaska, demonstrated that indigenous Arctic microorganisms effectively degrade both fresh and weathered oil. Most importantly, Arctic species and their counterparts in southern waters exhibit similar tolerance to dispersed oil and the use of dispersant was not observed to increase the toxicity of the oil (Gardiner et al., 2013).

Prince et al. (2013) recently suggested that biodegradation would be rapid and extensive when oil is present at concentrations expected with dispersant use. Subsequent mesocosm studies by McFarlin et al. (2014) with Arctic seawater collected from the Chukchi Sea, Alaska, incubated at -1°C , support this hypothesis. Indigenous Arctic microorganisms effectively degraded both fresh and weathered oil at environmentally relevant concentrations, with oil losses ranging from 46–61 per cent over 60 days.

The Norwegian Coastal Administration asked the Institute of Marine Research to present experiences, model simulations, and maps of marine resources as support for decisions related to mitigation of acute oil spills. The aim of the project was to present experiences for mitigations of acute oil spills using dispersants and to compare model simulations of overlap of fish eggs or larvae and an oil spill with or without use of dispersants in order to be able to give quantitative comparisons of these alternatives. The study used model simulations of a blow out of 4500 m³ (37,739 bbl) crude oil per day (Statfjord light crude) starting April 1 and lasting for 30 days at three locations along the Norwegian coast (The Haltenbank, south of Lofoten and Vesterålen). Spawning products were released (in the model) from the spawning grounds from 9 different sites, in the period from March 1st till end of April, and all spawning products were followed for 60 days from the time the spill starts independent of time for spawning. The study modelled overlap between spawning products and oil concentrations giving a total PAH concentration (TPAH) of more than 1.0 ppb ($\mu\text{g/l}$), generally sufficient to cause acute mortality. In addition the modellers used a threshold value of TPAH of more than 0.1 ppb, which is in the range

where sublethal effects are expected. Model simulations were performed with or without addition of the dispersants Corexit 9500. The results showed large variations in fraction of eggs and larvae from the different spawning grounds that experienced TPAH concentrations above the selected threshold values.

Model simulations from three different oil spill scenarios showed that addition of chemical dispersant could either increase or decrease fraction of eggs and larvae that were exposed above the selected threshold value. When the overlap of TPAH over threshold values from the three oil scenarios were modelled for all of the 9 selected spawning grounds, a general reduction in overlap was seen if dispersants were used compared to if not used.

These results showing that the use of dispersants does not result in dramatic differences on simulated overlap of fish larvae and oil compounds represents new information that needs to be considered when selecting strategies to mitigate an oil spill.

Oil-Mineral Aggregates (OMA)

In the marine environment, oil particles may not remain as discrete particles; they coalesce and rise back to the surface, or they can interact with suspended organic and/or inorganic particulate matter in the water column (Lee et al., 1985; Muschenheim and Lee, 2003; Owens and Lee, 2003) to form aggregate “flocs”, which include oil-mineral aggregates (OMA). The formation of OMA stabilises the oil-water interface, with the suspended particulate matter acting as a surfactant. This favours droplet formation and enhances natural oil dispersion into the water column.

The process of stabilising oil droplets with fine clay particles has led to natural and proactive oil spill remediation strategies for shorelines (Bragg and Yang, 1995; Lee et al., 2003a; Lunel et al., 1996; Owens, 1999). Breaking waves on the beach provide sufficient mixing energy to form OMA from fine sediments and spilled oil (Lee et al., 2003a). The OMA transport oil away from the shore, while simultaneously providing a microcosm for rapid bacterial biodegradation (Lee et al., 1998b; Stoffyn-Egli and Lee, 2002). OMA formation enhances the natural dispersion of

oil and reduces its environmental persistence (Bragg and Yang, 1995; Lee et al., 2003; Owens and Lee, 2003). Fine particles exist naturally in most coastal and many marine environments in sufficient concentrations for this process to occur naturally. This is the case on beaches so that the tactic of intentionally mixing oil with sediment that contains fine particles can be particularly effective (Owens et al., 2003; Shigenaka and Owens 2008).

Laboratory studies have shown that OMA can quickly form at near-freezing temperatures in seawater if high-energy mixing is applied (Cloutier et al., 2005; Khelifa et al., 2005). These results were confirmed in a mesoscale basin containing brackish water with slush and broken ice, in which 20-30 minutes of mixing dispersed about 50% of the spilled oil (Blouin and Lee, 2007; Cloutier and Doyon, 2008). These trials were reproduced at full scale in January 2008 in the St. Lawrence River when 1.7bbl (200 litres) of fuel oil were mixed with chalk fines by an icebreaker propeller (Lee et al., 2009a; Lee et al., 2011a). The oil dispersed into the water column and did not resurface. A control test with no added particles produced significant resurfacing oil. Water samples analysed in the laboratory revealed that OMAs were formed and that more than half of the total petroleum hydrocarbons had degraded after 56 days of incubation at 0.5°C (Lee et al., 2012).

Promising New Response Concepts for Dispersion and Biodegradation

The Macondo response demonstrated that large-scale subsea dispersant injection is potentially a very effective response measure to mitigate the effects of a subsea wellhead blowout in both temperate and Arctic waters, with or without ice present. A major benefit of direct subsea dispersant injection is the ability to continuously respond without being impacted by darkness, extreme temperatures, strong winds, rough seas, or drifting ice. Because of the high efficiency associated with adding dispersant directly to fresh oil at the discharge point under highly turbulent conditions, the dispersant volume can be substantially less (five times or more) than a surface application, a key advantage given the long

and difficult logistics resupply chain in most Arctic areas (Brandvik et al., 2013; Johansen et al., 2013). An additional significant benefit to applying dispersants subsea at an early stage in a response to a subsea blowout is the rapid reduction in hazardous (VOC) concentrations encountered by responders at the sea surface working to cap and secure the well.

A comparison of response effectiveness showed that direct injection could disperse oil at rates significantly higher than those achievable by aerial dispersant application or other response methods (Federal Interagency Solutions Group, 2010).

Based on research performed in a variety of mixing regimes, it is expected that a significant percentage of the oil discharged from the Macondo well was converted at the discharge point to droplet sizes below 100 microns, resulting in stable dispersion with minimal resurfacing (e.g., NRC, 2005; S.L. Ross and MAR Inc., 2007; S.L. Ross and MAR Inc., 2008; Reed et al., 2009). More work is required to understand the effectiveness, systems design, and short- and long-term impacts of subsea dispersant delivery.

Mullin (2012) summarises a number of dispersant research studies undertaken by the current Arctic Response Technology JIP. This program recently released an initial report summarising the status of dispersant regulatory approval and conditions on the application of dispersants in different Arctic nations (SEA Consulting, 2013).

Concerns over the resurfacing of oil dispersed under ice are also being addressed by the Arctic Response Technology JIP (Mullin, 2012). Scientists in Norway, USA, France, and Canada are assessing whether turbulence levels in the water column of the Arctic Ocean are sufficient to keep oil suspended for a sufficient time for effective biodegradation to occur. The assessment uses a combination of analytical modelling using actual water column profiles, new field data collection on natural turbulence levels under ice, and flume test data to determine whether dispersed oil with representative drop size distributions would remain suspended for long periods under an ice cover. Future decisions to use dispersants on spills in ice should take into account this type of assessment. Results are



Figure V-4.4 OSRL Boeing 727 in the process of being certified for dispersant application (2014)
(Source: OSRL).

expected for public release and publication in peer-reviewed journals in late 2014.

For dispersant application in ice-covered waters, newer gel formulations that are less toxic due to reduced solvent concentrations are currently being developed by industry. The gel formulation could increase the window of usability. Future possibilities include spraying gel on oil that rises to the surface of the ice in the spring rather than igniting it, or adding gel dispersant to oil discharged from a surface blowout onto an ice cover (Nedwed et al., 2011). This concept hinges on the ability of the dispersant to remain with the oil until it re-enters the water when the ice melts in the spring.

Future approaches to enhance oil biodegradation also include the application of nutrient-bearing treatment products (Kjeilen-Eilertsen et al., 2011) and the application of surfactants to surf-washing operations to increase the production of oil droplets and promote OMA formation nearshore.

A recent effort involves the development of a B-727 (Fig. V-4.4) jet aircraft-based dispersant delivery systems that can significantly reduce the mobilisation time and increase the application rate beyond the current Lockheed C-130. This system was created in association with Oil Spill Response Limited at the recommendation of the International Association of Oil & Gas Producers' (OGP) Global Industry Response Group (GIRG). The Boeing 727 was selected because of its high transit speed, large payload, and extended range, which offer the possibility of effective response to spills in remote settings where other equipment may be less readily deployed. As of April 2014, the aircraft is ready to deploy but not fully operational (OGP, 2011; OGP and IPEICA, 2012; OSRL April 2014).

Faster aircraft could significantly improve response times to a major arctic incident. A potential drawback is that the 727 requires significantly longer field lengths for fully-loaded take-offs than its propeller driven C-0130 predecessor, limiting the number of available Arctic airfields that would be suitable as staging bases. As with any aerial application system, operations are limited to daylight hours under conditions of good visibility and adequate cloud ceiling. Visibility, persistent fog, and cloud ceilings can be a constraint throughout the year and these limitations become increasingly severe during the fall and winter with limited or no daylight. These limitations become particularly challenging in the case of spills occurring during much of the ice growth season at high northerly latitudes and during the winter in Northern Europe.

Chapter V-5 Controlled Burning

- In situ burning (ISB) in open water and snow and ice-covered environments is a safe, environmentally acceptable, and proven technique with numerous successful applications in large-scale field experiments and accidental spills over the past 40 years.
- ISB is especially suited for use in the Arctic where ice often provides a natural barrier to maintain the necessary oil thicknesses for ignition, without the need for booms.
- Presence of a minimum oil film thickness for the type of oil (increasing by a factor of ten from light crudes and products to heavy crudes and fuel oils) is the primary limitation governing the success of ignition and burning. Other factors can limit the overall effectiveness, for example the degree of emulsification, waves, strong winds, and slush or brash ice mixed with the oil.
- Ongoing research combines the aerial application of proven herding agents and ignitors to create a new rapid response tool for spills in open drift ice where the ice concentrations are insufficient to maintain a burnable film thickness.
- US Federal and State agencies have developed comprehensive burn guidelines that lay out procedures to avoid any risk to responders or local populations.
- There is a large body of research that shows burning to be environmentally safe in terms of smoke particulates and gases, carcinogens (PAHs), and residue aquatic toxicity.
- In situ burning is not accepted as a permissible or desirable response tool by all Arctic nations. For example, there is no established approval process to implement burning in the Russian Arctic, or off Greenland. Implementation of burning has been used in a number of past incidents in the Baltic but it is not viewed generally as a primary response technique.

The first recorded use of ISB as a response countermeasure technique was in 1958 during a pipeline spill in the Mackenzie River, Northwest Territories, Canada. Important early experimental work was carried out on sea ice by the US Coast Guard (USCG) in Alaska in the 1970s (McMinn, 1972). A number of large-scale experiments successfully used ISB on oil that surfaced in spring melt pools after being spilled beneath the ice and trapped through a full winter. These experiments were carried out in the Canadian Beaufort Sea in 1975, 1980, and 1981 (e.g., Norcor, 1975; Dickins and Buist, 1981; Brandvik et al., 2006). Fingas (1998) tabulates over 40 cases where burning was employed in accidental spills and experiments over a 40 year period, 1958 to 1998. Since then, a series of dedicated Arctic experiments have successfully burned oil on solid ice and in pack ice on Svalbard and in the Norwegian Barents Sea (1993, 2008 and 2009). A number of historical examples involved burning oil spilled from vessels on and in ice, for example: *Othello/Katelsysia*, Sweden 1970; *Imperial St. Clair*, Canada 1979; and the *Edgar Jordain*, Canada 1983.

Overall removal rates in these field studies ranged from 65 to over 90%, depending mainly on the size distribution of the melt pools. In an experimental spill under solid ice in Svalbard in 2006, 28.5bbl (3.4 m³) of crude

oil were allowed to surface naturally through the ice and then burned with an overall removal efficiency of 96%. A portion of this oil was exposed to weathering on the ice surface for over one month before being successfully ignited (Brandvik et al., 2006). Despite these highly successful test results over four decades, concerns remain that actual spill conditions could reduce the effectiveness of ISB to far below these theoretical maximums (e.g., WWF, 2010; Goodyear and Beach, 2012). In practice, experiences with very large burns at sea demonstrate that efficiencies increase with scale, as the oil is pulled into the burn area by strong radial inflow winds at the surface. The influx of air feeding the burn acts to continually thicken the remaining slick. This effect was readily apparent in the massive ISB operation during the Macondo response and has been observed in large-scale experiments with burning oil on ice (Buist et al., 1994; Mabile 2012).

Similar high efficiencies were documented for ISB of oil mixed with ice within fire-resistant booms during the 2009 SINTEF Oil in Ice Field Experiments (Potter et al., 2012). In the same project, oil that was allowed to drift and weather in very close pack ice for over a week (Figure IV-1.5) was also successfully ignited and burned (Sorstrom et al., 2010).

ISB was used successfully on a trial basis

during the *Exxon Valdez* response (Allen, 1990). In 1993, a US-Canada experiment off Newfoundland successfully burned crude oil in fire-resistant booms in the open ocean and monitored a large suite of environmental parameters including smoke composition, residue toxicity, and upper water column impacts (Fingas et al., 1995).

Most recently, the massive ISB operation in response to the Macondo blowout resulted in a unique set of full-scale operational data that are applicable to response planning for Arctic offshore areas in the summer. Approximately 400 controlled burns removed an estimated 220,000 to 310,000 barrels (26,233 to 36,965 m³) of oil from the Gulf of Mexico. This was the first large-scale application of burning in an operational setting (Allen et al., 2011; Mabile, 2012).

With the opportunity to use aerial ignition systems such as the Helitorch, multiple oiled pools can be ignited quickly over a wide area. In open water and light ice (or managed ice) conditions up to several tenths (10-20% ice coverage), burning with fire booms provides a valuable alternative strategy that can occur simultaneously with mechanical recovery. Burning oil with natural containment provided by the ice in higher concentrations provides a unique way to eliminate oil quickly, efficiently and safely at times when continued use of booms is not possible and when ice stability and bearing capacity prevent safe on-ice operations. In intermediate ice concentrations when there is too much ice for booming and too little ice for natural containment, herding agents offer great promise in being able to thicken slicks to permit efficient ignition and burning (see discussion following). The spring and summer conditions when daytime air temperatures are above freezing constitute the most ideal operating conditions to consider the application of herding agents.

Experience with burning fresh, weathered, and emulsified oils and petroleum products in a range of ice conditions has led to some basic “rules of thumb” (Buist et al., 2003). The most important parameter that determines the likelihood of success and expected removal efficiency is the oil thickness. In order to achieve 60-80% removal efficiency in most situations, the starting thickness of crude oil needs to be

in the order of 3-5 mm. With relatively fresh oil that is wind-herded against an ice edge or on melt pools in the spring, removal efficiencies in excess of 90% are achievable.

The rules defining the minimum thickness needed to ignite and sustain combustion as well as other limiting factors are summarised as (Buist et al., 2003a):

- 1 mm oil thickness for light crudes and gasoline.
- 2-5 mm oil thickness for weathered crudes and middle-distillates (diesel and kerosene).
- 10 mm oil thickness for residual fuel oils and emulsified crudes.
- For a given spill diameter, the burn rate in calm conditions is about halved on relatively smooth frazil/slush ice and halved again on rougher, brash ice.
- Wave action within the ice also tends to reduce the burn rate.
- The oil to be ignited should not exceed an emulsification of ~25% water-in-oil.
- Ignition is most likely to be successful when winds are below ~19 knots (10 m/s).
- Cold air temperatures are not an impediment to successful ignition.
- Ignition is easiest with fresh, unemulsified oils, a condition more likely to last for a longer period of time in the Arctic as result of lower weathering rates.

Close pack ice (6/10 ice concentration or more) can enhance ISB by maintaining the original as-spilled thickness and preventing subsequent thinning through spreading (Buist and Dickins, 1987). See Fig. V-5.1 below.

In very open drift ice conditions, oil spills can rapidly spread and become too thin to ignite. Fire booms can collect and keep slicks thick in open water; however, even light ice conditions make the use of booms challenging (Bronson et al., 2002). In spite of these challenges, Potter and Buist (2010) reported highly effective (~90%) burning of oil within small ice pieces and brash collected within a fire-resistant boom during 2009 field experiments in the Norwegian Barents Sea (Figure V-5.2). Ice concentrations in these tests were between 1/10 and 3/10 ice concentration and large open areas, with small boats used to



Figure V-5.1 Aerial and surface views of burning crude oil spilled in slush between floes during the 1986 Canadian East Coast “Oil in Pack Ice” experiment (Buist and Dickens, 1987) (Photos: l: R. Belore, r: D. Dickens).

corral the needed quantities of ice (Potter et al., 2012). Burning under these conditions is subject to the same constraints affecting any response operation that depends on booms for containment, high sea states and excessive towing speed can lead to rapid oil loss through splash over and entrainment beneath the boom skirt. In addition, strong winds that are usually associated with rough seas can prevent successful or sustained ignition.

Following a successful test burn during the

Exxon Valdez spill (Allen, 1990), considerable effort went into developing new fire-resistant and fireproof boom designs (Allen, 1999). The American Society of Testing and Materials began developing standards associated with ISB in the late 1990s (ASTM, 2009), while the USCG produced an operations manual that details considerations and steps to be taken for open water ISB with fire booms (Buist et al., 2003b).

Several different types of fire booms were tested during the Macondo oil spill, with some notable differences in their effectiveness for oil retention and durability in the face of fire intensity and sea state (Allen et al., 2011; Mabile, 2010 and 2012). A number of these boom designs were successfully deployed in ice in 2008 and 2009 during the SINTEF Oil in Ice project (FigureV-5.2).

In the case of spills in solid ice nearshore, the choice of whether to burn on site or remove the oil to shore depends on the time of year, ice conditions and water depth. Ice roads cannot be safely constructed to access deeper water sites in the fast ice zone. For example, on-site burning might become the preferred option late in winter when there would be insufficient time to transport the recovered oil to shore prior to break-up. During this time, the preferred response tactic would be selective burning of oil on melt pools with aerial ignition.



Figure V-5.2 Burning crude oil spilled into a field of small ice cakes collected in a fire-resistant boom – Norway 2009 (Potter et. al 2012).

ISB Environmental Impacts and Safety Issues

Public opinion continues to play a major role in determining which response strategies are acceptable in any given situation, regardless of what the facts and science may prove. The successful implementation of ISB requires good communication and education of responders, regulators and the public to prove that it is safe and warranted in a particular case. In spite of initial resistance and scepticism, the large-scale application of burning in the Gulf of Mexico was very successful, removing more than twice as much oil than was achieved with mechanical containment and recovery teams and with a small fraction of the resources. That incident proved that it is possible to implement ISB in a region with large populations. Of course, attempting the same activities much closer to shore and in full view of local residents would be much more problematic. ISB has an important role to play in any response arsenal. No one strategy is a panacea under all circumstances. Oil spill response plans need to be flexible so that responders have access to all possible options as conditions dictate.

The short-lived smoke plume emitted by a burning oil slick on water is often the main ISB concern to the public and regulators, as low concentrations of smoke particles at ground or sea level can persist for a few kilometres downwind of an ISB. In practice, smoke particulates and gases are quickly diluted as the plume drifts and expands downwind. There are concerns about the impacts of visible soot deposition and possible interaction with marine mammals such as polar bears or foxes. In a series of burn experiments on ice in the Canadian Beaufort Sea, no visible on-ice soot deposition has been observed away from the actual burn site (author's personal experience).

Most of the oil in an in-situ burn is converted to carbon dioxide and water. Within the plume, there are several compounds that are of concern: particulate matter (soot composed primarily of elemental ("black") carbon); gases such as carbon dioxide, carbon monoxide, nitrogen oxides, sulphur oxides, and volatile organic hydrocarbons. The typical breakdown of in-situ burning by-products of

crude oil is as follows (modified from Ferek et al., 1997): 9%-15% particulate matter; 83%-89% gases (including water vapour); 1-10% floating residue; and <1% water soluble fraction.

Scholz et al. (2004) conducted an extensive study of all aspects of in situ burning as a response tool. That report provides a detailed discussion of field measurements, concluding that surface level particulates and hazardous gas concentrations are well below human health levels of concern.

Although the gases may be of higher abundance, they are of less concern than the soot (particulate matter) that is emitted. The black smoke consists of particles of solid materials (dusts, soot, fumes) or liquid material (mists, fogs, sprays) that remain suspended in the air long enough to potentially be inhaled by response personnel or the general public. Inhaled, they can cause respiratory problems, although the duration of exposure and particle concentration are important in determining effects. Respiratory problems usually involve high concentrations of particulates: in the order of several milligrams of particulates per cubic metre of air. In general, data from previous ISB research has shown that particulate concentrations in the plume only are of concern to public health within a few kilometres downwind of the burn location. The gases created during the burn typically dissipate to background levels within two to three kilometres downwind (Barnea, 1995).

Particulate size plays a crucial role in determining the length of time airborne burn residues are suspended in the air. Larger particulates (tens of mm in diameter) precipitate (settle or rain out) typically quickly and close to the burn site. Smaller particulates (ranging from a fraction of one to several mm in diameter) tend to stay suspended in the air for longer periods and can be carried over longer distances by the prevailing winds. Particulates small enough to be inhaled (particulate matter, 10 microns or smaller [PM-10]) may also remain suspended in the air for long periods of time. Due to plume dynamics, the concentration of PM-10s decrease as the plume rises and spreads and only those particulates that remain near the ground (the zone in which people breathe air), threaten the population

downwind. Public exposure to these plume components is minimal, unless the smoke plume is transported at ground level.

In the 1990s, research efforts assessed the potential environmental impacts of ISB, primarily from smoke plume and burn residues (Fingas et al., 1995). Work by Canadian and U.S. teams advanced the understanding of smoke constituents and how to predict downwind environmental impacts and to gather data for verification of existing plume models (McGrattan 1998). This research included a series of medium-scale burns at fire test facilities in Alabama, a series of burns at Prudhoe Bay in 1993, and a highly documented large-scale burn at sea off the Canadian East Coast in the same year (the Newfoundland Oil Burn Experiment – NOBE) (Fingas et al., 1995) (FigureV-5.3).

The NOBE burn provides controlled monitoring results for a large suite of all the critical environmental parameters, including smoke composition (carcinogens, PAH etc.), residue toxicity, and upper water column impacts (Fingas et al., 1995). Results demonstrate that, when conducted in accord with established guidelines, ISB is safe and poses no unacceptable risk to human populations, wildlife or responders. PAH concentrations were much lower in the plume and in particulate precipitation at ground level than in the initial oil composition, suggesting that PAHs are largely consumed by combustion.

Numerous agencies, primarily in the United States, have established guidelines for the safe implementation of ISB as a countermeasure. For example, the U.S. National Institute of Standards and Technology, NOAA, and Environment Canada have developed computer models that can be used to predict safe distances for downwind smoke concentrations. In 1994, the Alaska Regional Response Team (ARRT), comprised of multiple state and federal agencies, incorporated ISB guidelines for Alaska into its Unified Response Plan, becoming the first Arctic area to formally consider ISB as an oil spill countermeasure (Alaska Regional Response Team, 2008). Their guidelines are considered the most fully developed to date. The American Society of Testing and Materials began developing standards associated with ISB in the late 1990s

(ASTM, 2009), while the USCG produced an operations manual that details considerations and steps to be taken for open water ISB with fire booms (Buist et al., 2003b). The American Petroleum Institute (API) developed a guide to in-situ burning for decision-makers that summarises much of the available knowledge pertaining to impacts and procedures for mitigating and avoiding human health issues during an actual response (Scholz et al., 2004). Buist et al. (2013) provide an exhaustive summary of the state of knowledge surrounding the use of in-situ burning in the Arctic, including operational procedures to monitor the smoke plume and select safe distances from human populations to avoid any health concerns.

The burn residue refers to the unburned portion of the original spill remaining on the water surface when the fire extinguishes naturally. Burn residue generally appears as a viscous taffy-like substance that can easily be picked up in nets or with shovels and pitchforks.

Burn residue was also studied in the 1990s. For example, Daykin et al. (1994) and Blenkinsopp et al. (1997) reported on the burn residue's potential for aquatic toxicity. Bioassays show very little or no acute toxicity to oceanic organisms for either weathered oil or burn residue. These findings of little or no impact were validated with further studies by Gulec and Holdway (1999).

An industry-funded research program examined the likelihood of burn residue sinking as it cooled. Results show that residue from many crudes remain neutrally buoyant for some time, allowing mechanical recovery. Burn residues from efficient burns of heavier crude oils <32 °API may sink once the residue cools, but their acute aquatic toxicity is very low or non-existent (Buist and Trudel, 1995; S.L. Ross, 2002). Field tests conducted in Canada and the US over the past 40 years with a wide range of crudes (Alaska North Slope, Norman Wells, Norwegian etc.) have encountered no instance of residue sinking before it could be recovered over the course of a few hours. In response to public concerns about this issue, the Alaska Department of Environmental Conservation (2001) stated that:

The environmental advantages of in situ burning outweigh the potential environmental drawbacks of burn residue, including the possible environmental harm if the burn residue sinks. Therefore, the on-scene coordinators do not need to consider the potential impacts of burn residue when deciding whether to authorize an in situ burn. Nevertheless, the responsible party or applicant is required to have a plan for residue collection.

Following this approach, the Unified Command during the Macondo spill elected not to expend valuable resources recovering residue from the highly effective burns being conducted in the hundreds. Prince William Sound Regional Citizens Advisory Council (2004) further considered the potential risks to marine life posed by burn residues as being extremely low. They stated:

Alaska North Slope crude burn residues were composed almost exclusively of high boiling point fractions (HBPF). From an environmental perspective, the burning removes most if not all of the lower- molecular weight aromatic hydrocarbons, which tend to be the more toxic and more bio-available components of the crude oil (Fingas and Punt, 2000).

Historical research also studied the overall mass balance of polycyclic aromatic hydrocarbons (PAHs) consumed and created by ISB. During the Newfoundland Oil Burning Experiment, PAH concentrations were much lower in the plume and in particulate precipitation at ground level than they were in the initial oil composition, demonstrating that PAHs are largely consumed by combustion (Fingas et al., 2001).

Climate and Air Emissions Impacts of Burning

Concerns are often raised not only about human health issues related to burning oil in situ but also the long term environmental consequences, for example, melting ice through soot deposition and air emissions (principally CO₂). Experiences with tracking and documenting downwind deposition to the ice from actual field burns have not found any

measureable evidence of soot fallout, using cards on the ice as well as close-up observation of the snow cover (Dickins, pers. comm. 2014 from direct experience with a series of burns on ice in the Beaufort Sea in 1975 and 1980). These results agree with plume modelling and observations of burns at sea (e.g. Fingas et al., 1995).

The issue of climate change and related impacts of using ISB in an oil spill response operation can be approached in a number of ways.

Firstly, the oil or petroleum product burned in an emergency in the Arctic most would have been burned in some fashion anyway: a power plant, ship's engine, automobile, or truck somewhere in the world. In that regard, the emergency burning does not constitute a net global CO₂ emission.

Secondly, the emissions from short-term, rarely executed emergency burns are insignificant in volume compared to regularly occurring natural burns. For example, as calculated in Ferek and Allen (1993), the volume of added particulates and gases emitted from a burn of 10,000 barrels (1,192 m³) per day contributes approximately the same volume of CO₂ as a 2 acre slash burn (Laursen et al., 1992) and the same total smoke particles as a 7 acre slash burn (Evans et al., 1992). Looking at the pattern of recent wildfires only in the US for example, total acres burned in 2011, 2012, and 2013 were 8.7, 9.3 and 4.3 Million acres respectively (Source: National Interagency Fire Center https://www.nifc.gov/fireInfo/fireInfo_stats_totalFires.html). If the recent Macondo oil spill response is considered as representing the largest application of deliberate ISB to date, the entire suite of 400 burns produced approximately as much CO₂ as a fire burning 62 acres or as many total particulates as a 217 acre wildfire. Comparing these values to the US or worldwide extent of natural wildfires on an annual basis, it quickly becomes evident that the infrequent use of ISB in an emergency situation can have no measureable impact on global climate or climate change.

Promising New Concepts for Improving ISB

The Helitorch was originally developed for the U.S. Forest Service to set deliberate fires, and was adopted by oil spill responders in the 1980s as a means to ignite oil slicks at sea and on ice (Allen, 1987). This is a proven, safe device that has been considered an operational tool for Arctic spill response for over 30 years (Figure V-5.3). In the mid-1990s, new formulations for Helitorch fuel improved the ignition of emulsified and hard-to-light slicks. The Helitorch can be found in the inventories of a number oil spill response organisations charged with responding to spills in ice, for example ACS in Alaska and the North Caspian Oil Company (NCOC).

In spite of these historical successes and proven safety record, many aviation departments operating under modern, stringent standards of hazard assessment are reluctant to approve the use of the Helitorch system, especially off vessels. In addition, there are severe limitations to deploying helicopters long distances offshore with sling loads: slow speed when slinging and limited range; need for twin engines; susceptibility to icing, etc.

More recently, gelled delivery systems with the potential to operate at much higher speeds from a fixed-wing aircraft were tested in ground trials (Preli et al., 2011). API is sponsoring a program with the U.S. Forest Service and the US Navy to evaluate safer, more effective alternatives to the Helitorch (on going as of 2014). The Arctic Response Technology JIP also has as one of its research priorities the development of new aerial ignition systems for arctic offshore use that don't require a sling load under a helicopter (Mullin, 2012).

There are simple proven systems that can be used from the surface to ignite contained oil in booms or among ice floes. Most of these involve some combination of ignition source such as a flare and gelled gasoline as was used very successfully in the Macondo response, released from small boats updrift of the oil-filled boom. Consideration is also being given to using the new generation of economic unmanned air vehicles as possible disposable ignition devices or as a means of deploying ignitors into multiple oil pools.

In 2004, a multi-year joint industry and



Figure V-5.3 Open water burning of crude oil in a fireproof boom after ignition with a Helitorch during the Newfoundland Offshore Burn Experiment in 1993 (Source: Environment Canada).

government (Minerals Management Service, the predecessor of BOEM now BSEE) project began to study oil-herding chemicals to thicken slicks for ISB, as an alternative to booms in open drift ice conditions. Small-scale laboratory experiments were followed by mid-scale testing in large basins. The cold-water herder formulation used in these experiments proved effective in significantly contracting oil slicks in brash and slush ice concentrations of up to 70% ice coverage. Herded slicks in excess of 3 mm thickness were routinely achieved, and were ignited and burned at air temperatures as low as minus 17°C. Burn efficiencies measured for the herded slicks were only slightly less than the theoretical maximums achievable for equivalent-sized, physically contained slicks on open water (Buist et al., 2011).

The concept of using herding agents to burn free-drifting oil slicks in pack ice was successfully field tested for the first time in the Norwegian Barents Sea in 2008 as part of a JIP on Oil Spill Contingency for Arctic and Ice-Covered Waters (Buist et al., 2010) (Figure V-5.4). Burn removal effectiveness in that test was estimated to be in the order of 90%. The residue floated readily and was recovered manually from the water surface and ice edges. Buist et al. (2011) summarize past research into chemical herders and conclude that oil spill responders should consider utilizing them to enhance ISB in light to medium ice concentrations.

Another new ISB project planned under the Arctic Response Technology JIP (Mullin, 2012) includes the validation and testing of an operational airborne application system for chemical herders using both manned and robotic helicopters. The JIP is also initiating a

Figure V-5.4 Photo sequence showing before and after shots during the first field test of herders under arctic conditions in Norway, 2008 (Photos: DF Dickins).



Before application



9 min later



Est. burn efficiency 90%



new project (2015) to evaluate the potential of chemical herders under different oil properties and weathering, as well as investigating windows of opportunity for their use and any environmental impacts of the herding agents themselves. An important operational consideration when considering the use of herders is that they are not effective under freezing conditions, that is, with ice actively forming on the water surface. The combination of herders and ISB as an Arctic response tool is most applicable to conditions of very open drift ice in

the spring or summer when air temperatures are above freezing. At present, experience with using herding agents to thicken spills in ice is limited to a series of laboratory and basin experiments and the relatively small-scale experimental releases in 2008 in Norway. There is no indication at this stage that herders would work any less effectively on much larger spills and hopefully, future testing can expand the scale and provide conclusive documentation to support this expectation.

Chapter V-6 Summary of Marine Spill Response Effectiveness

- Encounter rate, how much oil a particular countermeasure can intercept or treat in a given time, is a critical factor in determining the overall response effectiveness.
- Another important factor, is the necessary response time to achieve a reasonable chance of success at recovery. The presence of ice can contain the oil, slow the spreading and theoretically buy responders valuable time before the slick is spread thinly over widely dispersed open water areas.
- For the different response strategies, the overall effectiveness depends on the speed of advance (e.g., vessels towing boom at less than 1 knot, aircraft speed), the swath or sweep width (e.g., boom opening, aircraft or vessel spray arm width), burn removal rate, and skimmer recovery rate, among other factors, such as the possible need for lightering and decanting.
- These basic principles apply equally to spills in open water or ice however both the speed of advance, the swath width and recovery rate can be negatively impacted by the presence of any significant ice cover. These constraints are particularly acute with response strategies requiring the deployment of booms and skimmers.
- All response strategies dependent on surface or airborne systems (burning, booming, dispersant application, skimming) are seriously constrained or halted by darkness, fog, low visibility and in the case of flying activities, low cloud ceilings.

Positive and Challenging Aspects of Responding to Spills in Snow and Ice

There are both positive and challenging aspects associated with spill response operations in an ice and snow environment for planning and executing an effective response. Potential positive factors tied to operational practicalities are:

- The wind and sea conditions in many Arctic areas are considerably less severe than most open ocean environments, facilitating marine operations. The presence of any significant ice cover dampens wave action and often limits the fetch over which winds might otherwise create larger fully developed waves.
- Growing ice can potentially encapsulate and isolate oil from the marine environment for many months, providing valuable additional time for planning and executing a response when conditions are more favourable.
- When ice concentrations preclude the effective use of traditional containment booms, the ice itself often serves as a natural barrier to the spread of oil. The resulting smaller contaminated area not only reduces the potential marine impacts but limits the operational area that must be covered by response crews.
- The fresh condition of encapsulated oil when exposed at a later date (e.g., through ice management or natural migration/melt) enhances the chances for effective combustion and/or dispersion.
- The interaction of individual ice floes in intermediate ice concentrations can increase the available natural mixing energy and promote successful dispersion.
- The fringe of land fast ice common to most Arctic shorelines acts as an impermeable barrier and prevents oil spilled offshore at freeze-up from entering and contaminating sensitive coastal areas throughout the long winter period.
- Long periods of extended daylight during much of the summer oil exploration period increase the operational time for response activities.
- The natural containment provide by ice can provide responders with additional planning and mobilization time, a key advantage compared to often having only hours to deal with a rapidly spreading spill in open water.

At the same time, there are a number of potentially serious response challenges associated with responding to spills in ice and snow covered areas, including:

- Accessing oil trapped on or under ice offshore in moving pack is very difficult, especially where crews cannot safely maintain sustained operations on the ice without continuous, reliable and immediate means of evacuation.
- Difficulty in detecting oil under ice with existing technology.
- The presence of ice generally limits or prevents the effective use of traditional mechanical cleanup methods in responding to large spills.
- Difficulty in finding and accessing oil trapped on or under moving ice offshore.
- Potential need to supply additional mixing energy in high ice concentrations to promote dispersion.
- Lack of oil spreading within slush and brash-filled leads and openings in the pack ice significantly decreases oil flow to the skimmer, and along with freezing of pumps, fittings and hoses, makes skimming operations extremely difficult.
- Potential gelling of crude oils with pour points at or below 0°C.
- Extended periods of winter darkness and low visibility prevent visual spill detection and monitoring, and affect all aspects of response operations including aviation activities associated with spotting and surveillance, dispersant application and burning.
- Lack of ports or approved disposal sites severely limit the ability to deal with large volumes of recovered oily waste in remote areas of the Arctic (Baltic excepted).
- The general lack of infrastructure in most Arctic offshore areas requires that oil industry operators, and ship owners be either entirely self-sufficient in their ability to support an extended spill response operation or have the means to cascade resources rapidly into the region through pre-arranged agreements.
- Maintaining worker safety, with the potential for extreme wind chill and fatigue.

Operational Limits and Recovery Rates of Countermeasures

The knowledge gained from laboratory, tank, and field experiments under Arctic conditions can be used to determine operating limits for different countermeasures (Potter et al., 2012). However, operating limits by themselves are not good indicators of response effectiveness. Actual removal rates depend on a many inter-related factors, such as oil thickness, degree of emulsification, sea state, wind speed, weather, darkness, and the availability of experienced aerial spotters to guide marine crews to the thickest parts of a slick, etc.

Calculating the expected recovery or removal rate for a particular response effort is a complex process, with no simple method to estimate spill response effectiveness. Instead, past experience with particular spills can help to assign ranges of expected recovery effectiveness for specific countermeasures.

The previous discussion has drawn attention to the limitations of mechanical recovery in ice. These conclusions are based on having to deal with a subsea blowout involving high volume flow rates during exploration, or a large tanker incident. For smaller, more frequent spills especially in areas with developed infrastructure such as the Baltic Sea, mechanical recovery would continue to play an important role as the primary and preferred option in many situations.

Net environmental benefit analysis (NEBA) can help responders, regulators, and stakeholders decide which oil spill response options could be recommended or advised against in a given situation. The principles of applying this type of analysis are discussed further in Part II-4.

The following general guide summarises the applicability of the various response options under different scenarios and oil in ice situations, assuming that there is enough daylight and acceptable weather conditions to permit safe operations. These points are not meant to be all inclusive as there is tremendous variability in the likely source of spills and ice/climatic conditions in different Arctic areas.

Natural containment of oil in ice occurs with:

- Oil spilled into the water between floes:
 - Any time of year in concentrations consistently greater than ~6/10 ice concentration (60% area coverage).
 - More likely with grease, nilas or new ice at freeze-up than summer pack ice.
- Oil deposited on top of the ice (e.g. surface blowout).
- Oil deposited under ice.

Natural migration of oil through the ice is likely:

- When sea ice warms in the spring, typically late March to June depending on latitude (e.g. Svalbard versus Beaufort Sea). Note: there is insufficient knowledge to predict migration rates of oil through brackish ice at more southerly latitudes, for example the Baltic Sea.
- When the ice is less than 20 cm during the early freeze-up period (depends on brine volume and ambient temperatures).

Mechanical recovery by skimming is possible:

- Using booms for containing large spills into the water:
 - As long as regional ice concentrations are ~1/10 ice concentration or less (classified as open water). Booming is still possible in ice concentrations up to ~3/10 but the challenges of changing course frequently to avoid larger floes means that the boom spread needs to be fairly limited, resulting in a relatively small swath width and encounter rate compared to similar operations in open water. Principal constraints are sea state and oil properties. Main drawbacks are limited encounter rate, very high resource demands, offshore storage limitations and oily waste disposal. Recovery rates are highly variable depending on the extent of oil spreading and spill size.
- Small localised spills without booms – pockets of concentrated oil in the water among drifting ice:
 - Effective in ice concentrations over 6/10 (oil naturally contained by ice).

- Not effective with very open drift ice less than ~5/10 ice concentration where the oil spreads at similar rates and to similar thin films as in open water.
- State of the art ice capable skimmers and ice cleaning systems, such as those developed in Finland, can be used in ice concentrations up to 90-100%, with the proviso that the ice thickness is less than 0.5-0.7 metres and the ice blocks are 2 X 2 metres or smaller. This type of ice condition is typical of that found in ship channels with frequent passages, in the Baltic Sea for example.
- For localised spills under or on top of stable landfast ice:
 - Effective as long as the ice is stable and able to support surface vehicle access to shore to move recovered fluids or oily snow.

In situ burning without fire booms:

- For small to large spills into water between floes:
 - Possible with ice concentrations over 6/10, becoming increasingly effective as concentration increases and spreading decreases.
 - Possible with herding agents in lower ice concentrations as long as air temperatures are above freezing, that is spring or summer.
- For large spills onto the ice surface (e.g. surface blowout):
 - Effective with aerial or surface ignition (if the ice provides a safe working surface) or as long as there is sufficient oil film thickness. With rapidly drifting ice, oil films may be too thin to ignite. Oiled snow can be concentrated on the ice surface for burning but this can only be achieved on landfast ice nearshore that provides a safe working surface and enables access by mechanised equipment.
- For large spills under ice in the presence of gas (subsea blowout):
 - Possible with new or young ice at freeze-up when rupture of the ice sheet over the blowout is likely, exposing concentrated oil for ignition. Effectiveness is dictated by the degree of emulsification

and film thickness (affected by water depth).

- Possible with warm porous ice in the spring as long as oil films on the surface are thick enough to support combustion. Overall effectiveness is highly variable and a major logistics challenge, potentially having to deploy aerial igniters along a meandering ice drift track over long distance, hundreds of kilometres or further.
- Not possible with thick, consolidated ice in winter (oil remains trapped underneath or encapsulated within the ice).
- For large spills under ice from a batch release such as pipeline rupture:
 - Effective with new or young ice at freeze-up, or warm ice in spring and summer (oil surfaces as thick films suitable for rapid removal by aerial ignition).
 - Effective with stable nearshore fast ice where mechanical equipment can be

used to expose the trapped oil for burning in ice sumps or trenches.

- Possible offshore if thick pockets of trapped oil can be located and exposed by helicopter-supported crews and lightweight drilling/cutting equipment. Detection is the main challenge in this scenario.

Dispersants:

Potentially effective in a range of ice conditions with the available turbulent energy at the surface through inter-floe collisions. High ice concentrations (e.g. >7/10) may require the addition of mechanical mixing energy, for example using icebreaker drive units. In the case of a subsea release under significant ice cover, the majority of the spill would be inaccessible to direct aerial application of dispersants, but direct injection at the wellhead remains a viable and potentially effective option.

Dispersants are not likely to be approved for use in shallow, contained sea areas.

PART VI – Coastal Response in Ice and Snow

Chapter 1: Shoreline Assessment and Shoreline Treatment Decisions

Chapter 2: Shoreline Treatment Strategies and Options for Oiled Ice and Snow

- Acquiring information on the location and character of the oil and the ice and snow conditions is a necessary first step in the process of scaling a shoreline response and deciding where and how to treat oiled shorelines.
- This information is used to develop a strategic shoreline treatment program that includes defining cleanup end points and selecting appropriate treatment techniques.
- The objectives of shoreline cleanup are to minimise the effects of spilled oil on resources at risk and to promote and accelerate natural recovery.
- In remote areas, the selection of appropriate tactics for oiled ice and snow conditions has to be combined with the practicality of minimising the level of manual effort and minimising the volume of waste generated by the treatment actions. These objectives lead to a preference for *in situ* shoreline treatment tactics.

Chapter VI-1 Shoreline Assessment and Shoreline Treatment Decisions

- Systematic air and ground surveys provide information on the location and character of oiled shorelines. The protocols for shoreline segmentation, a technique used to provide information for planners and operations that were developed for ice- and snow-free shorelines, require adaptation when ice and snow are present.
- The survey techniques are the same as used elsewhere in the world and face the same challenges for detecting and delineating subsurface oil when in ice and snow. Trained dogs have demonstrated the ability to locate oil in ice and buried in beach sediments.
- Treatment standards and end points should be based on the concept of Net Environmental Benefit as it relates to the resources at risk and the potential effects of treatment actions (particularly in tundra environments).

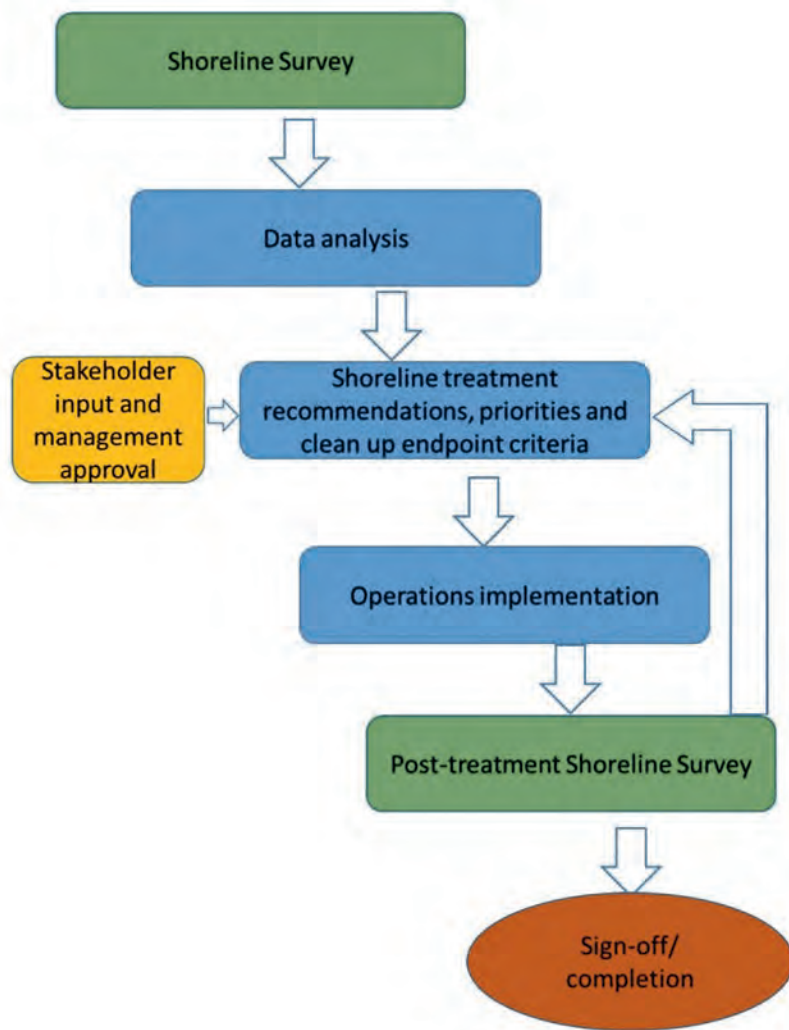


Figure VI-1.1 *Shoreline response program steps.*

The overall sequence of actions and decisions related to oil in the coastal environment, for spills of any size or location, is outlined in Figure VI-1.1.

The first step in all coastal oil spills is for a shoreline assessment survey (often referred to as the Shoreline Cleanup Assessment Technique, or SCAT process) to generate information so that decision makers in the spill management team can develop response objectives and strategies (IPIECA 2014). The shoreline cleanup decision process involves the development of agreed cleanup priorities, strategies, end point(s), and agreement on the process by which these decisions are made and on the inspection process that ensures the decisions are implemented and the desired end point is achieved. The shoreline response decision process in any environment includes:

- a. Locating, delineating and describing the oil on the shore, ice, or snow;
- b. Evaluating response priorities;

- c. Determining the consequences of treatment strategies and tactics;
- d. Estimating volumes and types of wastes generated by the response options;
- e. Agreeing on treatment end points;
- f. Agreeing on appropriate treatment options; and
- g. Defining the sign-off process.

a. Oiled Shoreline Assessment Surveys and Segmentation

An essential first step of an oiled shoreline assessment (or SCAT) survey is to divide the coastline, lake shore or river into working units called segments, within which the shoreline character is relatively homogeneous in terms of physical features and sediment type. Segment boundaries are established on the basis of:

- Prominent geological features (such as a headland);
- changes in shoreline or substrate type (beach versus bedrock, or changes in ice and snow character);
- Changes in oiling conditions;
- Jurisdictional and administrative boundaries; or
- An operations area.

This georeferenced system provides a geographic framework within which all subsequent data collected and treatment recommendations are referenced and compared through time.

Segments should be part of pre-SCAT planning and mapping or, in their absence, should be defined as soon as possible in a response. A “rule of thumb” for segmentation is to divide the coast or river on the basis of practical aspects that can be used by Planning or Operations teams to deploy cleanup crews.

- On a long uniform coast or river, or coasts where ice and snow form the shoreline character, a segment may be centred on access points with a segment boundary approximately midway between two access points.
- Alternatively, segments can be defined on the basis of distance. For example, segment

Snow or Ice Term	Abbreviation	Figure(s)
Snow	SNW	II-3.2B, H: II-4.11A, B, C
Frozen swash	FSW	II-3.2A: II-4.11A
Frozen spray	FSP	II-3.2C
Ice foot	IFT	II-3.2A: II-4.11A, B
Ice-push ridge	IPR	II-3.4C
Grounded ice floes	GFL	11-3.4A, B
Glacier ice	GLC	11-3.2F, G

Table VI-1.1. Standard terms for shore zone ice and snow conditions.

boundaries could be every 500 m or some other length alongshore or downstream along relatively homogeneous ice or snow shorelines with few to no distinguishing features.

The SCAT method is one procedure to detect, delineate, describe and document oil on the shore and has been adapted for use in cold climates and on shorelines with ice and/or snow (Owens and Sergy 2004). This technique is based on a systematic survey design and the use of standard terms and definitions to create an information base for the response team to decide which shorelines should be cleaned and how cleanup end points can be achieved without incurring environmental damage. In particular, a set of standard terms define the basic categories of shore zone ice and snow conditions.

The number of personnel involved in a SCAT program and the number of layers in the vertical structure of the SMT organisation are a function of the scale of the response and the necessary span of control. On a small-scale response, several roles may be filled by one person. On a large response, span of control is maintained by subdividing management activities vertically by inclusion of “deputy” or other management positions in the chain of command and/or horizontally by subdividing activities by function or by geography. The SCAT Coordinator is a member of the environmental team maintains strong links and communications with the operations team and the shoreline treatment supervisors.

SCAT activities following a spill typically can be divided into the **REACTIVE PHASE**, during which decisions and actions follow

pre-planned procedures and priorities or are developed according to the situation at hand, and the **PLANNED PHASE**, during which the actions follow incident-specific strategies and tactics that are developed on a rolling basis by the spill management team. In the Reactive Phase the SCAT program provides a rapid assessment of the scale and character of the affected area. The Planned Phase involves establishing priorities, recommending treatment techniques, and setting objectives that determine when operations have been completed.

b. Detection and Delineation in Ice and Snow

Surveys to delineate and document the presence of oil on the shore typically follow a systematic procedure that may involve an initial air or ground reconnaissance survey to locate and define the extent of the affected area followed by detailed ground surveys to delineate and describe the oiled locations and the oil distribution (IPIECA, 2014).

Oil on the surface of a shoreline or on ice and snow is easily detectable from the air or on the ground and delineation is straightforward. Aerial surveys are efficient and rapid for surface oil on ice and snow due to the distinct contrast.

The detection and delineation of oil on the shore and segmentation become significantly more difficult when oil:

- penetrates into or is buried by clean beach sediments;
- becomes incorporated within existing shore-fast ice and grounded floes;



Figure VI-1.2 Dog detection team locating buried oil on an arctic shoreline— Svalbard (Source: SINTEF).



Figure VI-1.3A Drilling through ice to detect subsurface oil (Photo credit: E. Owens).



Figure VI-1.3B Ice trenching across the intertidal zone (Photo credit: E. Owens).



Figure VI-1.3C Snow removal to detect subsurface oil in snow (Source: ECRC).



Figure VI-1.3D Snow removal on tundra to detect subsurface oil in snow (Source: Alaska Clean Seas).



Figure VI-1.3E Ground truth survey on a winter beach with snow (Photo credit: E. Owens).

- is covered by newly formed ice from the freezing of wave splash, spray, or swash;
- infiltrates into snow; or
- is covered and buried by wind-blown snow.

Oil within or below ice and snow is unlikely to be visible from the air so that initial reconnaissance surveys may rely on the detection techniques described in Part III, Section 3.

Ground truth surveys may be impractical for logistics or safety reasons, particularly where there is broken ice in the shore zone (Figure III-3.4A and B).

Dogs have been used for many years to detect subsurface oil pipeline leaks (Oil and Gas 2006) and field trials have demonstrated that they can successfully and rapidly detect even small amounts of oil covered by 0.5 m of ice and snow (Figure VI-1.2)(Brandvik and Buvik 2009, Dickins *et al.* 2010).

Typically, the search for subsurface oil during ground surveys involves a grid or other geometric pattern based on either working outwards from a source or from an observed surface oil patch (API 2013). Locating subsurface oil is challenging if no surface oil is visible. Digging pits in snow and trenches in ice or core/tube sampling are labour intensive and very time consuming, even using portable ice drills, probes, or ice trenching devices (Figures VI-1.3A and B).

The primary difference between pit or trench sampling and detection dog surveys is that spot sampling can easily miss subsurface oil unless the oil is present as large continuous layer, whereas detection dogs provide virtually continuous coverage and can detect individual patches of subsurface oil.

Figures VI-1.3C through D show response teams attempting to detect subsurface oil through snow removal on a frozen shoreline and tundra. Figure VI-1.3E shows a SCAT team conducting ground truth surveys along a winter beach with snow.

c. Treatment Standards, Clean-up End-Points, and Operational Closure

The development of treatment end points at the regional (strategic) and site-specific (segment) levels is a critical first step at the beginning of a response. End points may vary within a response depending on the variations within the affected area in terms of the character of the oiled shoreline and ecological or human use factors. The early development of end points is important as they:

- Define which oiled shorelines will REQUIRE TREATMENT and identify those oiled shorelines where natural degrada-

tion and weathering (natural recovery) is acceptable (NO TREATMENT), based on the risks within the time-frame of weathering processes.

- Determine the degree or level of EFFORT and help identify the appropriate TREATMENT TECHNIQUES required to achieve the end point targets.
- Define when treatment activities will be completed (NO FURTHER TREATMENT – NFT- is required) in situations where natural degradation and weathering are expected to achieve the end point(s) in an acceptable time period without additional actions.

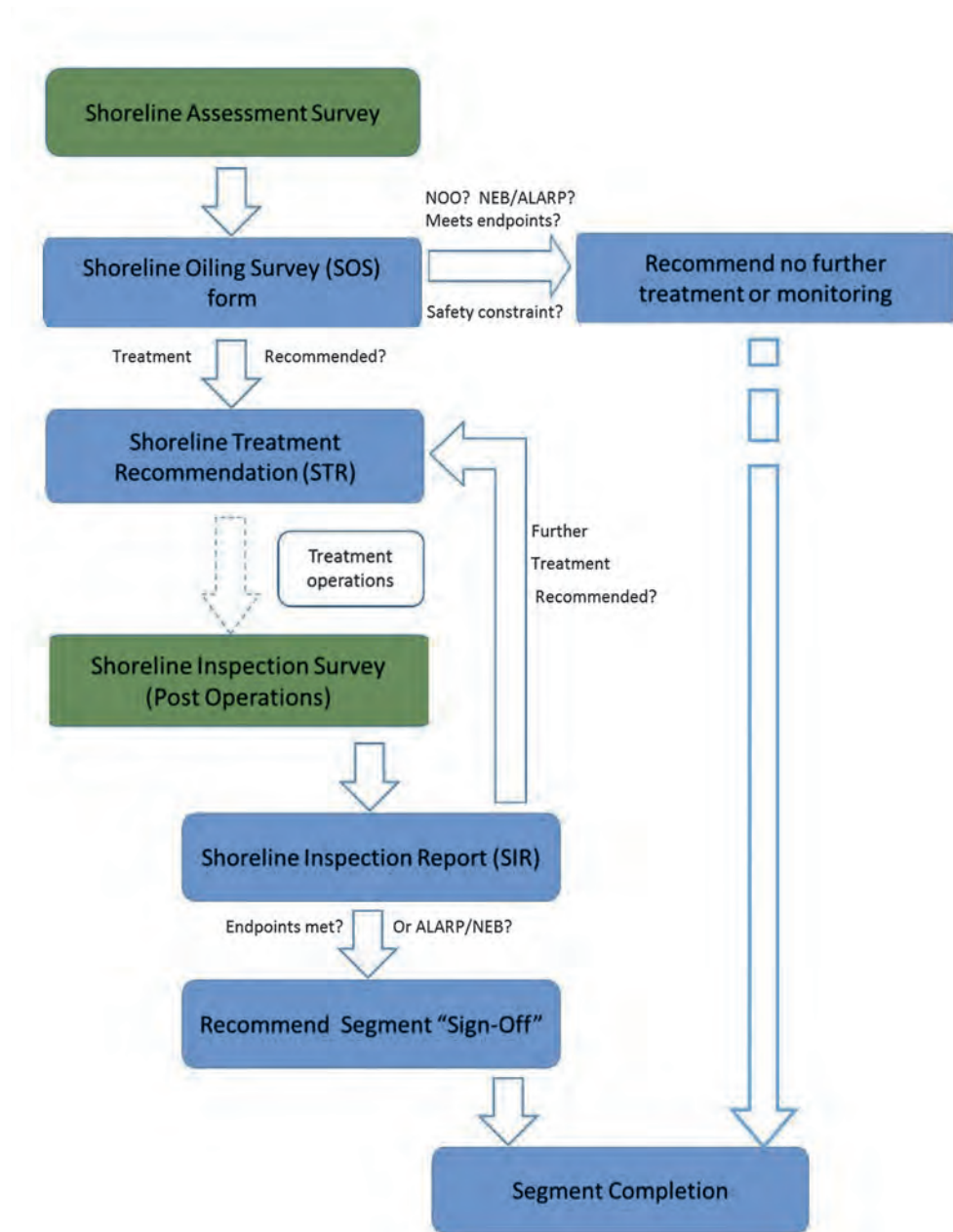
The decision process is rarely straightforward and balances environmental concerns, the needs of local communities, operational practicality, and safety (Baker, 1997). Frequently trade-offs are necessary. For example, tundra shorelines are sensitive to trampling and vehicle traffic during the summer but oil removal or treatment may be considered critical to protect wildlife.

The development of shoreline cleanup strategies and priorities involves an understanding of the effects of the oil and the consequences and effects of the intended treatment activities themselves. Studies on the Net Environmental Benefit (NEB) of shoreline treatment have shown that inappropriate response actions can cause more harm than the oil alone and can delay rather than accelerate recovery (Baker 1995) – see Part V, Chapter 4. The NEB concept is particularly important in ice-dominated cold climates where recovery would be expected to be slower and where vegetated tundra or wetland shorelines are highly susceptible to disturbance by human or vehicle traffic.

The typical sequence followed during a cleanup program, within the sequence of management and decision steps outlined in Figure VI-1.1 is shown in Figure VI-1.4.

Once end points and priorities have been established, work orders, sometimes in the form of a Shoreline Treatment Recommendation (STR) form, are generated that describe how the clean-up operation should proceed. The STR should also include clear instructions regarding any safety, logistical, ecological and

Figure VI-1.4 Sequence of activities that support the shoreline treatment decision process and the field operations.



historical/cultural issues and constraints (IP-IECA, 2014).

End points are the cleanup targets but the completion of cleanup activities (closure) can result from five different conditions:

- There is NO OBSERVED OIL or the oiling condition is BELOW the established end point(s) – so that treatment is not required.
- The agreed END POINT(s) has been met by the treatment program.
- NO FURTHER TREATMENT (NFT) is recommended as an assessment of the NET ENVIRONMENTAL BENEFIT(s) (NEB) indicates that, although the end point(s) has not been met, additional activities could result in a negative effect(s) or could delay recovery.

- A point is reached in the cleanup program referred to AS LOW AS REASONABLE PRACTICABLE (ALARP), a principle which means that further activity is feasible and practical, but has little or no value as the risks associated with the remaining oil are tolerable.
- A SAFETY issue(s) identified by command staff or safety managers may present an unacceptable risk for responders that cannot be mitigated.

Field survey teams work closely with the operations crews and, based on one of the five conditions listed above, agree and recommend that a segment does not require further treatment. In Figure VI-1.4 this step is the Shoreline Inspection Report (SIR) form, which

brings closure and enables a field operation to demobilise from that segment or area.

Chapter VI-2 Shoreline Treatment Strategies and Options for Oiled Ice and Snow

- The cold working environments associated with ice and snow bring significant operational, safety, and logistics issues that must be factored into the selection of treatment strategies and tactics for oiled ice and snow.
- The emphasis for shoreline cleanup strategies is on *in situ* treatment techniques that require minimal equipment and manpower resources, minimise operational risks, and generate little or no waste.
- Oil spilled onto an ice or frozen snow-covered shore may pose no immediate environmental threat during a freeze-up or winter season but may put resources at risk if released during the following melt or thaw season.
- Tundra treatment strategies and tactics must factor in the sensitivity to operational activities as surface disturbance can have long-lasting effects.

To a large extent, the same strategies and tactics used as best practice in warmer environments apply equally to the cleanup of oil with ice and snow in the shore zone. However, only a relatively small proportion of Arctic shorelines that have seasonal ice and snow are in relatively densely populated areas, such as the Northern Baltic Coast. Almost all coasts that have year-round ice and snow, in particular, glaciers, ice sheets, exposed tundra ice, and inundated tundra shore types, occur in remote areas and cold working environments which have significant operational, safety, and logistics issues (Part VII).

a. Objectives and Strategies for a Coastal Response in Ice and Snow

The general objectives of shoreline cleanup are to minimise the effects of spilled oil on

resources at risk and to promote and accelerate natural recovery. This is less a concern for exposed ice and snow in themselves as they do not support plants and are used intermittently by animal life, so that they are not considered to be environmentally sensitive shore types. Ice edges and land fast ice may be used as haul outs for marine mammals, but these locations are spatially and temporally variable.

Where tundra is present in a low-lying coastal/river flood plain or as part of an ice-rich exposed cliff, the vegetation could be oiled. Coastal tundra is a sensitive habitat for many migratory or nesting species and can be a zone that is important for subsistence activities. The environmental setting of a site and the adjacent areas, rather than the ice itself, are more relevant in a Net Environmental Benefit Analysis (NEBA), which considers the potential effects of oil spilled in the shore zone and the development of appropriate response objectives and strategies. Oil spilled onto an ice or frozen snow-covered shore may pose no immediate environmental threat during a freeze-up or winter season but may put resources at risk if released during the following melt or thaw season.

- The year-round environmental setting defines the risk(s) associated with oil in ice and snow and forms the basis for setting response objectives.
- The timing of the incident with respect to the ice and snow cycle is critical in the development of a strategic plan.

The key challenges for the development of a shoreline response program and plan in coastal environments with year-round ice and snow are associated with remoteness, safety and logistics. As a result, the emphasis for shoreline cleanup strategies is on *in situ* treatment techniques that require minimal equipment and manpower resources, minimise operational risks, and generate little or no waste. Oily waste incinerators have been developed for remote area use but lack the throughput capacity to deal with large volumes of materials.

The many individual tactics that can be used to treat or clean any shoreline types can be grouped into three basic strategies:



Figure VI-2.1 Oil in grounded ice floes (Source: ECRC).

- a. natural recovery without intervention;
- b. physical removal of oiled materials; and
- c. *in situ* treatment of the stranded oil.

b. Selection of Treatment Tactics for Shore Types with Ice and Snow

The selection of cleanup options depends on the character of the shore zone so that response strategies and tactics must be modified when ice and/or snow are present; for example, a shore with permeable coarse sediments in warm months can be replaced by a frozen ice, impermeable substrate in cold conditions (Figure III-3.1). When seasonal ice and/or snow are discontinuous, as would be the case, for example, with grounded ice floes, the selection process considers all of the oiled substrate materials. Thus one option(s) may be appropriate for oiled ice and snow and oth-

STRATEGY	TACTICS AND APPLICATIONS
NATURAL RECOVERY Natural cleaning is often the least damaging option for treating light and moderate oiling, particularly where access is limited or difficult, as is often the case in ice-dominated environments.	This strategy may be appropriate where: <ul style="list-style-type: none"> to treat or clean stranded oil may cause more (unacceptable) damage than leaving the environment to recovery naturally (NEB); response techniques would not be able to accelerate natural recovery; or safety considerations could place response personnel in danger either from the oil itself or from environmental conditions (weather, access, hazards, etc.).
PHYSICAL REMOVAL AND RECOVERY Physical removal involves the recovery and disposal of stranded oil. There is a range of tactical options to remove oil that basically involve either flushing or washing and recovery or manual or mechanical removal.	<ul style="list-style-type: none"> Flooding and washing move oil either onto the adjacent water where it can be contained by booms and collected by skimmers, or towards a collection area, such as a lined sump or trench, where it can be removed by a vacuum system or skimmer. This strategy is slow and labour intensive but generates only liquid wastes. Manual removal includes shovels and rakes as well as cutting oiled vegetation and the deployment and recovery of passive sorbents to collect oil. Manual removal is slow and labour intensive, but generates less waste than mechanical removal. Mechanical removal techniques essentially use equipment designed for earth-moving or construction projects, although a few commercial devices have been fabricated specifically for shoreline cleanup applications. Although cleanup rates are less labour intensive and are much faster than manual removal, which may be factors in remote areas, as much as ten times more waste is generated by mechanical removal, which in itself may be a logistics issue. <p>The recovery of oiled snow and ice can create large volumes of waste that contain only small amounts of oil (less than a fraction of a per cent by volume) and one option to minimise the waste stream is to melt and decant the ice or snow on site.</p>
IN SITU TREATMENT The <i>in situ</i> options involve treatment that is conducted on-site and minimises the generation or recovery of oiled waste materials that then must be transported and disposed (Owens <i>et al</i> 2009). <i>In situ</i> treatment is particularly suited for remote areas where logistics and waste management are major factors in operational practicality and feasibility.	The range of tactics includes: <ul style="list-style-type: none"> Mechanical mixing of oiled sediments (also known as tilling); Sediment relocation (also known as berm relocation or surf washing); Burning of oiled logs or organic debris (commonly used as these contain very small amounts of oil); or A group of chemical or biological tactics which involve the addition of agents to facilitate removal of the oil from the shore zone, or accelerate natural <i>in-situ</i> oil removal, degradation and weathering processes. Bioremediation is a practical option (Prince <i>et al.</i> 2000) although biodegradation rates are slowed in cold climates by temperature and limited nutrient availability and would not be practical over long lengths of oiled shorelines in remote areas.

Table VI-2.1 Summary of Shoreline and River Bank Treatment Tactics.

NATURAL RECOVERY

- Natural recovery is the preferred option on exposed coasts.
- Less appropriate for heavy oils or weathered crudes on a sheltered coast where the oil is likely to persist longer.
- May not be appropriate immediately before freeze-up as the oil could become encapsulated by the ice and potentially remobilised during the next thaw.
- When there is no physical energy to remove the oil, natural recovery does not take place until spring melt and breakup.
- Natural recovery is the safest option for volatile and light oils such as gasoline.

PHYSICAL REMOVAL

- Flooding or low-pressure ambient-water washing onto an adjacent water surface are practical and efficient for removing low to medium viscosity oil on shore-fast ice if the adjacent sea is ice-free and air temperatures are above freezing (Figure VI-2.2A).
- Washing techniques are preferable for volatile oils when conducted from a safe distance as fumes, fire, and flashback are risks to consider.
- Oil can be flushed onto the surface of the water for containment and recovery. This washing option can minimise ecological impacts that might result if stranded oil remobilised.
- Washing from a boat or barge is preferred if the water is deep enough. The edges of shore-fast ice are often steep so that washing from a boat or barge may be the only practical option.
- High-pressure, ambient-water washing and low-pressure, warm/hot water washing may be useful for more viscous oils that cannot be removed by low-pressure, ambient-water washing.
- Manual removal of medium and heavy oils is recommended for small amounts of oil, but safety is a primary concern on slippery ice surfaces.
- Mechanical removal may be efficient in some circumstances where equipment is available and can be deployed safely.
- Sorbents can be deployed to collect small amounts of low to medium viscosity oils. For example, rope mops can be deployed using cranes to sweep ice surfaces or to collect oil from pools, cracks, or crevices.
- Vacuums can be used to collect light and medium viscosity oils (Figure VI-2.2D).
- Ice melters used on site can effectively minimise waste volumes

IN SITU TREATMENT

- Burning of pooled or collected oil on the ice surface is applicable for all but the most viscous oils.

Table VI-2.2 *Treatment Tactics for Shore-Zone Ice.*

ers for oiled beach sediments or bedrock (see Figure III-3.5A).

Individual shoreline treatment and cleanup tactics are described in detail in field guides which specifically consider ice and snow (EP-PR, 1998; Environment Canada, 2010) or tundra (ADEC, 2010). This response guide summarises the recommendations provided by those field guides in the context of the selection of appropriate tactics for shore types that are associated with year-round or seasonal ice and snow (Chapter III-3c):

- Ice
- Inundated low-lying tundra
- Ice-rich tundra cliffs
- Snow.

The basic treatment and cleanup strategies are summarised in Table VI-2.1.

Treatment Tactics for Ice

As ice shorelines and ice surfaces are not sensitive, oil removal tactics on the ice itself do not usually have significant environmental effects.



Figure VI-2.2A Boom placed in an ice slot prior to flushing of oil from a shoreline ice surface (Source: ECRC).



Figure VI-2.2B Trench cut in ice to collect oil for recovery (Source: ECRC).



Figure VI-2.2C Manual recovery on ice (Source: ECRC).



Figure VI-2.2D Vacuum system to recover oil on ice surface (Source: ECRC).

Treatment Tactics for Inundated Low-lying Tundra

NATURAL RECOVERY

- Often the least damaging alternative for treating light and moderate oiling, particularly where access is limited or difficult, as is often the case with this type of shoreline. This may not be appropriate immediately before freeze-up as the oil would be encapsulated by ice and potentially remobilised during the next thaw.

PHYSICAL REMOVEAL AND RECOVERY

- Low-pressure, ambient water flooding and/or washing could raise the local water table to float and direct oil towards a boomed area for collection.
- Pools of mobile oil can be recovered using vacuum systems combined with booms and skimmers if the oil is not too full of debris or too viscous. Quickly deployed vacuum systems are particularly appropriate for thick pools of oil stranded in lagoons or ponds.
- Rope mops can be particularly useful and could be used to recover free oil on water surfaces or from the surface of water-saturated sediments where vacuum or disc skimmers cannot be deployed or are not effective. Vertical rope mops could be deployed from cranes or similar equipment. Manual tactics using shovels or rakes could be used in small, heavily oiled areas.
- Oiled vegetation could be cut, preferably only on dry tundra surfaces. Surface disturbance is minimised if treatment is done during winter months when the surface material is frozen (see "Tundra" below).
- Sorbents are effective for fresh crude oil and petroleum products. The most effective technique in a peat-rich environment might be to use natural peat as a sorbent and remove the most heavily oiled fraction. Peat is more effective on fresh crude oil and fuels than on aged oils. Dry peat should be used as peat moss becomes less oleophilic when wet. Although loose natural sorbents are less easy to recover than the oil alone, in peat-dominated areas, there may be no additional impact if all of the peat is not recovered as long as the most severely oiled patches of peat are recovered.

IN SITU TREATMENT

- No recommended options

Table VI-2.3 Treatment Tactics for Shore-Zone Inundated Low-Lying Tundra.

Treatment Tactics for Ice-rich Tundra Cliffs

Tundra cliffs are an eroding and often unstable coastal feature. Block falls, slumping, and mud flows are potential safety hazards during any response operations, particularly when cliffs are higher than 2 m. These events may occur suddenly and without warning.

Activities should be restricted to the base of the cliff whenever possible to prevent trampling or other damage to the tundra surface.

In many areas, the beaches that front a tundra

cliff are very narrow or absent so there may be little working area or room to stage equipment. Select cleaning techniques that minimise erosion. Although this is unlikely to cause significant environmental damage, the vegetation on the tundra is a living community.

Oil that has splashed over the cliff onto the top of a tundra surface is above the normal limit of wave action and is treated in the same manner as an on-land spill.

NATURAL RECOVERY

- Natural recovery is the preferred response option due to the rapid natural erosion of ice-rich tundra cliffs.
- Oil on the cliff face, at the top edge of a cliff, or in the tundra and peat deposits at the base of a cliff will probably be naturally removed within weeks provided that the oil is not stranded at the onset of freeze-up.
- Natural recovery may not be appropriate immediately before freeze-up as the oil would be encapsulated by ice and potentially remobilised during the next thaw.
- During periods of little wave action in the open-water season, the cliffs retreat as a result of warm air melting the exposed ice. At these times, oil removed from an eroding cliff by melting ice could be contained at the base of a cliff by a berm or passive sorbents.

PHYSICAL REMOVAL AND RECOVERY

- Oil could be washed from the cliff face by low-pressure ambient temperature water washing and contained and collected at the base of a cliff by a berm or passive sorbents.
- Flushing or washing activities may trigger unexpected block falls, slumping, or mud flows.
- As erosion of the cliffs by natural processes is normal, cleanup activities such as low-pressure washing that cause additional erosion of the cliff face are not considered to be damaging. Any erosion caused by cleanup should be minimised, however, as the vegetation on the tundra is a living community.
- Manual removal of oil or oiled tundra/peat at the base of a cliff is practical for small amounts of oil.
- Mechanical removal using a large or small front-end loader is more practical for larger amounts of oil or oiled material.

IN SITU TREATMENT

- Mixing and sediment relocation can be considered if these actions disperse oil without re-oiling the site of oiling adjacent areas.

Table VI-2.4 *Treatment Tactics for Shore-Zone Ice-Rich Tundra Cliffs.*

Treatment Tactics for Snow

NATURAL RECOVERY

- Natural recovery is usually preferred for light oils that will evaporate during thaw periods unless the oil spill is close to sensitive habitats or populated areas.

PHYSICAL REMOVAL AND RECOVERY

- If the adjacent sea is ice-free and air temperatures are above freezing, flooding or low pressure ambient-water washing may be practical to flush the oiled snow onto the water surface for containment and recovery.
- Manual removal with shovels and rakes may be appropriate for small amounts of surface or subsurface oil, but becomes less practical as the amount of oiled area and the volume of oiled snow increases.
- Light and medium oil pooled on the surface of a snow-covered area or collected in trenches or by containment berms can be recovered by vacuum systems.
- On flat surfaces, or if a mechanical arm can reach the oiled area, mechanical techniques can be used to scrape snow-covered areas for removal and disposal. These techniques could include melting to separate the oil and snow, or burning.
- Sorbents could be used to remove light or medium oil on the surface, but are less effective as the oiled area or volume of oiled snow increases or in low temperatures that cause the oil to either reach its pour point or fall below it.
- Snow melters used on site can effectively minimise waste volumes.

IN SITU TREATMENT

- Mixing may be appropriate for small or large amounts of light or medium oils. Wave energy levels in the intertidal zone would quickly weather the oil. Oil could be recovered by following sediment relocation with wet mixing and containment and recovery.
- Pooled oil on the snow surface, oil that is contained by berms, or oiled snow that is collected and piled in a suitable location can be removed by burning. This may be suitable in remote areas where minimising waste is an important consideration.

Table IV-2.5 *Treatment Tactics for Shore-Zone Snow.*

c. Tundra Treatment Strategies and Options for Oiled Snow and Ice

Tundra translates from Russian to treeless or marshy plain, and consists of low growing plants such as mosses, lichens, grasses, sedges and dwarf shrubs. The soil at a certain depth (the permafrost layer) remains frozen year-round, however the surface active layer, which freezes in the winter, will thaw during the summer to allow growth of the live vegetation mat. Tundra may be classified as: aquatic, wet, moist or dry. See Table VI.2-6 for the characteristics of the different types of tundra.

Oil could potentially spill within tundra environments, for example due to a release from an overland pipeline in the coastal zone, a spill on a river during flood conditions, or a spill on water during a storm surge. The behaviour and effects of oil on tundra depends on a variety of factors, including:

- Oil type and degree of weathering:
 - Toxicity
 - Viscosity
 - Smothering effects
 - Penetration into soil/sediment
 - Volatility/evaporation rate
- Tundra type:
 - Oil spilled onto dry or moist tundra which is unsaturated with water is more likely to penetrate into the active soil layer
- The presence of ice/snow
- The depth of the permafrost layer

Treatment and Operations

Treatment tactics used in oiled arctic tundra include:

- Manual removal of oil and oiled material
- Mechanical removal (e.g. lifting, scraping, brushing or cutting)
- Recovery of fluid oil with skimmers, vacuums and pumps
- Use of sorbent materials (including snow)
- Flooding with water to float oil
- Flushing with water to mobilise oil
- Trenching to intercept oil
- Burning oiled vegetation
- Cutting oiled vegetation

For restoration and rehabilitation tactics, see ADEC, 2010.

Consideration must be given to the management of snow, for example to access contaminated soil/vegetation underneath, to use the snow as a natural sorbent, to create a berm or barrier to prevent the spreading or movement of oil or to create a containment area, to place on a treated site to reduce desiccation, or to remove from a site in spring to accelerate the growing season.

Travelling on tundra

In some areas, such as Alaska, permits may be required for vehicles travelling off-road. Typically, tundra travel is allowed when the ground is sufficiently frozen that suitable vehicles can be used on the snow without significantly damaging the tundra beneath. Responders should follow any guidelines provided by the relevant agencies. For example, Alaska Department of Natural Resources (DNR) uses the following criteria:

- *DNR will implement tundra opening for general cross country travel in wet sedge tundra when a minimum 15 cm (6 inches) of snow cover is available and ground hardness reaches a minimum of 75 drops of the slide hammer to penetrate one foot of ground. At this combination of ground and snow conditions, no significant change in the depth of active layer, soil moisture, or vegetation composition and structure is anticipated.*
- *DNR has determined that once a minimum threshold of 23 cm (9 inches) of snow cover and a ground hardness of 25 drops of the slide hammer for one foot of soil penetration has been attained, general tundra opening in tussock tundra can proceed without a significant change in active layer depth, soil moisture, or vegetation community composition and structure.*

Vehicles with tracks (below left) or low ground pressure tires (below right), which are specifically designed for travel on snow and ice, are necessary for winter arctic tundra travel.

Aquatic Tundra			
Occurrence	<ul style="list-style-type: none">Frequently forms marshes along the margins of ponds, lakes and streamsMay form a mosaic with wet tundra		
Common plants	Arctic pendant grass, Water sedge, Mare's tail	Soils	Thick layer of aquatic sediments and peat.
Active layer	Deep at maximum thaw (summer). A thaw basin of unfrozen soil may be present in the vicinity of ponds, lakes and streams.		
Wet Tundra			
Occurrence	<ul style="list-style-type: none">Where shallow (<0.3 m) surface water persists through all or most of the growing seasonIn troughsIn low centres of polygonsIn wet areas within drained lake basins		
Common plants	Water sedge, Tall cotton grass, Fisher's tundra grass, Arctic pendant grass	Soils	A mat of roots and organic matter approximately 0.3 m thick, underlain by mineral soils. Ponds and saturated water are common within wet tundra areas, and soil pore spaces are saturated with water during the growing season.
Active layer	Moderate (0.3 m) to deep (1 m) at maximum thaw. High thermal conductivity of water may melt the top of permafrost in the summer		
Moist Tundra			
Occurrence	<ul style="list-style-type: none">Usually where soil is saturated in a portion of the active layer throughout the growing season, but standing water is absent or present for only a part of the growing seasonSlopes of hillsHigh-centred polygonsRims of low-centred polygons		
Common plants	Sedges, Cotton grasses, Dwarf shrubs (including willows, birch and mountain-avens)	Soils	A dense, compressed mat of roots and organic matter overlying mineral soils.
Active layer	Relatively thin due to the dense insulating organic mat and moderate soil moisture content		
Dry Tundra			
Occurrence	<ul style="list-style-type: none">Where good drainage creates relatively dry soil conditions throughout the growing seasonOn the slopes of mountain rangesOn ridges and hilltops in foothillsStabilised sand dunes, pingos		
Common plants	Dwarf shrubs (including birch, willow, mountain-avens, blueberry and cranberry) Labrador tea, Crowberry, Arctic bell-heather, Bearberry, Lichens, Mosses, Grasses	Soils	Thin root mat and low organic matter content compared to soils of moist and wet tundra. Ample drainage reduces the ability of the thin root mat to hold moisture.
Active layer	The active layer in dry tundra is usually comparable to wet and moist tundra, but can be as deep as 1 m.		

Table VI-2.6 *Characteristics of the four different tundra types (adapted from ADEC, 2010).*



Figure VI-2.3 Left: Husky 8. Right: Rolligon (Photo credits: E. Owens).

Tundra operations: Issues and Best Practices

Operating in arctic tundra often presents logistical and technical difficulties, due to:

- Remote locations
- Low temperatures
- Short summer season
- Patterned ground features (polygons)

In addition, tundra is particularly sensitive to disturbances such as physical damage to

vegetation and root systems, changes to the hydrology (for example due to excavations or compacted ground), changes to the thermal regime (for example due to removal or addition of snow, or cutting of vegetation) or thawing of the permafrost layer.

The following table (Table VI-2.7) summarises key issues and best practices associated with travelling and staging; and operations:

	Potentially damaging actions	Best Practices
TRAVEL/STAGING	<ul style="list-style-type: none"> • Repeatedly walking over the same area when the active layer of soil is thawed • Driving vehicles or heavy equipment on tundra when the active layer of soil is thawed • Repeatedly driving vehicles or heavy equipment over the same area at any time 	<ul style="list-style-type: none"> • Limit foot and vehicle traffic as much as possible • Avoid following the same path repeatedly (enter and exit the site from different path, if possible) • Use existing roads (gravel, peat or snow) as much as possible • Use snow ramps to access tundra from gravel roads and pads • Use existing gravel and ice pads for staging where possible • Use plywood or interconnecting rig mats as boardwalks or working platforms for light equipment • Use snowshoes when repeated trips on foot cannot be avoided
OPERATIONS	<ul style="list-style-type: none"> • Excavating, vegetation cutting or trenching • Using high-pressure and/or hot water to flood • Injuring the root mat while burning or scraping, especially when the soil is very dry 	<ul style="list-style-type: none"> • Limit use of invasive treatment tactics as much as possible • Replace displaced tundra sod back into original divot, or transplant tundra sod to replace soil and vegetation that have been removed • Restore natural contour and drainage by filling excavations

Table VI-2.7 Best practices for working in tundra environments (adapted from ADEC, 2010).

Part VII – Oil Spill Response Safety for Operations in Ice and Snow

Chapter 1: Principles of Safe Operations
Chapter 2: Risk Identification and Mitigation
Chapter 3: Job Safety Analysis

Chapter VII-1 Principles of Safe Operations

- Safety of personnel is always paramount
- Operational and safety challenges posed by long periods of darkness and extreme temperatures, that are typical in marine and coastal environments with ice and snow, require a continuous process of risk assessment

Safety risks to personnel in environments with ice and snow are primarily physical or mechanical in nature, ranging from weather and temperature extremes to ice hazards and equipment or vehicle (including boat and helicopter) operations). All activities should follow safety procedures to identify and mitigate risks, typically through a Job Safety Analysis (Chapter VII-3 below).

Potentially the greatest risk for outdoor works is associated with extremes of temperature. The following basic points apply to any cold weather work on shorelines or offshore in cold weather with ice or snow present.

Cold weather Injuries can be mitigated by

recognising the three main factors involved with cold impacts on the human body:

1. Temperature
2. Wind (chill)
3. Wet conditions with potential for rapid hypothermia if immersed

The combination of these three risk factors controls the rate of heat loss and risk loss of life if not prevented by appropriate clothing and attended to immediately.

Outdoor clothing for field operations in cold weather should incorporate a system of three layers as well as hand, head and foot protection:

- Base (inner layer – wicks moisture away from the skin).
- Middle wear insulating layer (possibly several depending on how extreme the conditions).
- Waterproof outer layer providing protection from wind, rain, and snow.

Other important elements in planning for a safe working environment include:

- Ample hydration (the Arctic and many extreme ice environments can be extremely dry).
- Buddy system of working in teams to check on frostbite and respond to any emergency.
- Safety equipment as demanded by the operation, such as hardhats, personal flotation, safety boots, emergency locator beacons, safety lines, medical kits etc.
- Warming shelters such as temporary tents on shore or on the ice.
- Safety checklists and briefings before going out.

Numerous documents provide detailed information on mitigating against cold (Gudmestad 2010) and on personnel safety for ice and snow conditions, for example the “Guidelines for the management of Work in Extremes of Temperature” (NZ, 1997), IPIECA/OGP, 2008 and CDC, 2014, and the Alaska Clean Seas Technical Manual (ACS, 2013). Tactic L-7 in that manual contains information on work/warm-up cycles, wind chill charts, ice thickness guidelines and working load information important for operating vehicles safely on ice. These guidelines should be combined with checklists, such as:

- ILO Hazard Datasheets; and
- Best practice guidelines, such as IPIECA/OGP 2012a (Oil Spill Responder Health and Safety) for the types of activities or tasks to be undertaken.

Many spills have been cleaned up safely in the past. Because clean-up activities are usually conducted in the open air, the hazards from vapours and gases are relatively low, and simple protective clothing can reduce contact with oil and minimise any chance of harm (IPECA, 2012a). Refer to further discussion of the necessary steps to protect worker health through a job safety analysis in Chapter VII-3 below.

In November 2014, the IMO Maritime Safety Committee (MSC, 94) adopted a mandatory International Code for Ships Operating in Polar Waters (Polar Code), with related amendments to the International Convention for the Safety of Life at Sea (SOLAS). This international code covers the full range of design, construction, equipment, operational, training, search and rescue and environmental protection matters relevant to ships operating in the inhospitable waters surrounding the two poles. Although not specific to the safety of oil spill responders, this new code does embrace all aspects of crew safety on-board vessels in extreme climatic conditions, including icing.

Chapter VII-2 Risk Identification and Mitigation (checklists)

The topic of risk management is addressed at many academic and operational levels (for example, NAS 2005; CAA Offshore Helicopter Operations <http://www.caa.co.uk/default.aspx?catid=2657>).

In brief, risk mitigation and planning

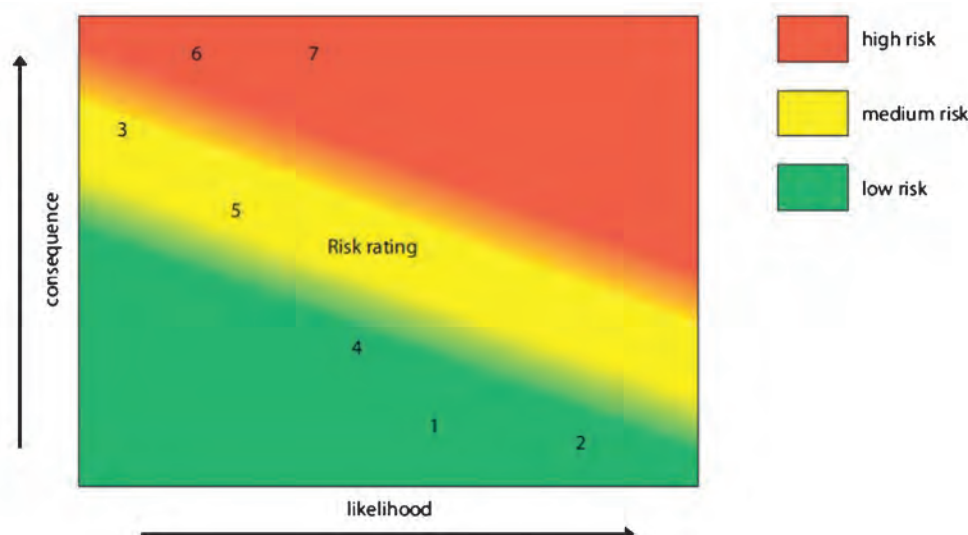


Figure VII-2.1 Example of a Risk Assessment Matrix (RAM) that might result from an analysis of seven individual tasks or scenarios (Source: IPIECA/OGP 2014).

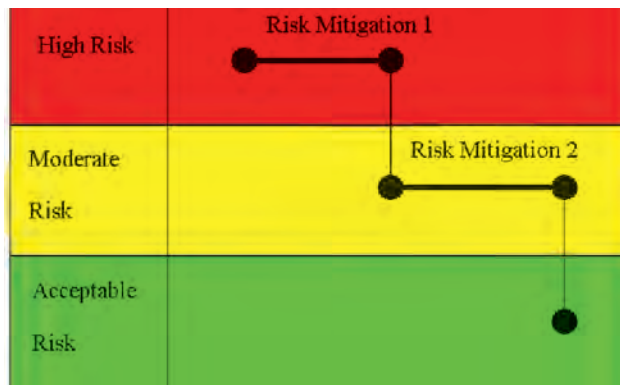


Figure VII-2.2 “Water-fall” diagram that shows the progression of a risk as mitigation actions are applied (Source: NAS, 2005).

explore risk response strategies for the high risk activities. The process identifies and assigns parties, either manager or individual personnel, to take responsibility for each risk response. This ensures that each risk requiring a response or mitigation has an “owner”.

The major steps in determining the appropriate risk management strategies include the following (NAS 2005):

- Development of risk awareness;
- Project risk identification;
- Qualitative risk assessment;
- Quantitative risk assessment;
- Risk prioritisation;
- Risk mitigation; and
- Active, ongoing risk management.

Risk identification is an integral part of several elements of a project or task planning and design that include:

- The statement of work;
- Work breakdown structure;
- Budget;
- Schedule;
- Acquisition plan; and
- Execution plan.

A common tool for risk assessment is a matrix which plots the likelihood (probability) and consequence (impact) outcomes from individual activities, such as working outside or operating equipment on ice. This diagram plots relative values to assist in the planning and mitigation process:



Figure VII-2.3 Training exercise on ice at -10°C with appropriate PPE and shelter (Photo credit: E. Owens).

Mitigation can involve a range of actions (NAS 2005) such as:

- TRANSFERING (for example, assignment of a task to a specialist or specially trained team/individual)
- BUFFERING (making something stronger or more durable than would be normal)
- AVOIDING (changing the scope of work or the parameters of a task or activity)
- CONTROLLING (PPE, or early warning systems)

The “waterfall” diagram (Figure VII-2.2) illustrates the process by which a risk is mitigated so that it changes sequentially from “high” to “moderate” to “low” risk. As an example, in extreme cold temperatures the health risks to an individual outside worker can be mitigated by avoidance, such as delaying the activity until temperatures rise if the consequence is likely to be high (hypothermia, frost bite). Similarly, journeys can be rescheduled if an existing or forecast white-out situation or high seas make land or sea conditions risky. A moderate risk can be buffered or controlled through the use of appropriate sheltering or clothing (PPE) so that the activity can be conducted with a low likelihood of a health impact (“acceptable risk”).

Chapter VII-3 Job Safety Analysis

The first task in assessing site safety is for the management team to carry out a high-level risk assessment of the overall situation as soon as possible to ensure that oil spill responders or the wider population are not in danger. The initial approach should be to answer such questions as:

- Is there a potential gas cloud and therefore an explosion risk?
- Should people be evacuated or excluded?
- Is the environment safe for people and responders?
- Will oil enter water systems that may affect people?

This initial safety assessment may lead to the establishment of safety or exclusion zones

whilst the area is monitored in more detail. This evaluation may include the use of monitoring equipment to detect flammable or toxic gases and materials. The persistence of these types of hazards is not usually great, but this issue is more significant with the more volatile oil types and in calm weather conditions. Monitoring should continue until it is established that the risk has reduced to acceptable levels. Once the overall situation has been stabilised from a safety point of view then the work of responding to the oil spill can begin. In normal circumstances responders are not likely to be exposed to areas in which there is an explosion or toxic vapour risk. Specialist source control teams, who are trained and equipped to work within these high-risk areas, are the ones most likely to enter such high risk areas.

An IPIECA report deals specifically with responder health and safety (IPIECA 2012a) and discusses the issue of toxicity faced by responders who could come in direct contact with the oil. Fears of the toxicity of oil are widespread but the risk is low because, although oils contain potentially harmful components, mitigation is relatively easy to prevent these entering the body to cause harm. The spilled product’s toxic properties may follow a variety of routes of entry into the body other than breathing the gases or vapours. It may be absorbed through the skin or eyes, ingested (swallowed) or injected.

The potentially most serious exposure exists during the initial stages of a spill, particularly when volatile crude oils, condensates or light refined products are involved. These products can have carcinogenic components. For example, benzene is a confirmed human carcinogen for which the risks and safe exposure limits have been defined. If the potential exposure exceeds the prescribed limits, then suitable PPE must be worn, such as chemical protective clothing and respirators. Although these aromatic products usually only persist for a short period of time and will rapidly disperse in the air, they do pose a specific safety risk. Care must be taken to monitor the levels of benzene in the environment and protect both responders and the public from exposure. The level of aromatics released will be a function of the specific oil type, the surface

area of the spill, the temperature, and the wind conditions at the time of the release. The risks must be assessed by specialists and controls implemented to reduce their impact to an acceptable level.

Reference to the occupational exposure limits (OELs) of any chemicals should be made and a proper monitoring regime adopted. OELs may be either short-term (for chemicals with acute effects) or long-term (for chemicals with chronic effects).

A Job Hazard Analysis (JHA), Job Safety Analysis (JSA) or a Job Task Analysis (JTA) is a tool used to identify hazards associated with a task or activity and to implement controls or best practices to mitigate those hazards.

A JSA/JHA can be:

- Task Specific, that would be related to a one-time or routine, repetitive action or activity; or
- Area Specific, and relate to the environmental conditions and hazards of a location where an activity may take place (such as climate, bears, etc.).

JSAs/JHAs are used to educate and train personnel on safe practices prior to utilising equipment or undertaking any task that could present safety hazards or concerns. A JSA/JHA can involve the following questions regarding a proposed activity:

- What materials, equipment or tools are involved?
- What can go wrong?
- Where could this happen (environment)?
- How could this happen?
- Who or what is this hazard going to affect (exposure)?
- What precipitates the hazard (trigger)?

- What outcome could occur should this happen (consequence)?
- Are there other contributing factors?
- Is a permit required for this activity?

If materials are involved in the task, a Material Safety Data Sheet (MSDS) for those materials would be part of the safety or hazard analysis.

Two elements of the process are Site Safety Briefings and Site Safety Survey Checklists (IPIECA, 2012a) to ensure that environmental conditions are evaluated, hazards and risk identified and mitigations measures set in place.

The objective of the analysis is to identify, then reduce or eliminate the risk or hazard. Once identified, mitigation can be achieved by:

- Engineering exposure controls:
 - Isolate the person/people from the hazard (for example, when wind chill exceeds a certain temperature)
 - Change the work space layout
 - Substitute less hazardous materials or tools
 - Physically modify the equipment
- Administrative exposure controls:
 - Change how the task is performed
 - Reduce the frequency or length of time for the task or activity
 - Train to recognise hazards and employ safe working practices
- Use of personal protective equipment, such as gloves, hearing protection, or changes in the type of personal protective equipment.

Table VII-3.1 is a simplified sample template for a JSA.

Job Title: Job Location: Analyst: Date:			
Task # A	Task Description: Walking on sea or river ice		
Potential Hazards: <ul style="list-style-type: none">• Ice properties• Air temperature and wind speed• Fatigue	Hazard Description: <ul style="list-style-type: none">• Ice too thin to support weight of person(s)• Snow cover masks ice cracks• Wind chill• Poor visibility – “white out” conditions		
Consequence: <ul style="list-style-type: none">• Slip on ice• Fall into an ice crack• Ice failure and fall though ice• Hypothermia	Hazard Control Measures: <ul style="list-style-type: none">• Pre-deployment on-site environmental and safety review and checklist• Anti-slip boot attachments and appropriate cold-weather gear• Snow and ice probes to measure snow/ice thickness• Safety officer monitors air temperature and wind speed, consults wind-chill chart, monitors personnel behaviour and performance• Standby rescue team; ice bridge(s) or ladders; warming shelter		
Rationale or Comment: <ul style="list-style-type: none">• Understanding and knowledge of ice properties and characteristics should be part of all training programmes• Walking on ice involves identifiable risks that can be mitigated under prescribed environmental conditions			

Table VII-3.1 *Sample JSA Template.*

(NOTE – this example is intended only to provide examples of topics in a typical JSA and does not identify all hazard types nor the full range of mitigating actions).

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- <http://www.nasa.gov/topics/earth/features/icesat-20090707r.html>
- <http://www.ktva.com/ghost-barge-in-russia-now-544/>



Annex A – Oil Classification

CLASSIFICATION OF OILS ACCORDING TO THEIR SPECIFIC GRAVITY

Group 1 oils

A: *API > 45 (Specific gravity < 0.8)
B: Pour point °C
C: Viscosity @ 10–20°C: less than 3 CSt
D: % boiling below 200°C: greater than 50%
E: % boiling above 370°C: between 20 and 0%

	A	B	C	D	E
Asgard	49	-28	2 @ 10°C	58	14
Arabian Super Light	51	-39	2 @ 20°C		
Cossack	48	-18	2 @ 20°C	51	18
Curlew	47	-13	2 @ 20°C	57	17
F3 Condensate	54	<-63	1 @ 10°C	81	0
Gippsland	52	-13	1.5 @ 20°C	63	8
Hidra	52	-62	2.5 @ 10°C	60	11
Terengganu condensate	73	-36	0.5 @ 20°C	>95	0
Wolffbutt	49	-53	2 @ 20°C	55	4
Gasoline	58		0.5 @ 15°C	100	0
Kerosene	45	-55	2 @ 15°C	50	0
Naptha	55		0.5 @ 15°C	100	0

Group 2 oils

A: *API 35–45 (Specific gravity 0.8–0.85)
B: Pour point °C
C: Viscosity @ 10–20°C: between 4 Cst and semi-solid
D: % boiling below 200°C: between 20 and 50%
E: % boiling above 370°C: between 15 and 50%

Low pour point <6°C

	A	B	C	D	E
Arabian Extra Light	38	-30	3 @ 15°C	26	39
Azeri	37	-3	8 @ 20°C	29	46
Brent	38	-3	7 @ 10°C	37	33
Draugen	40	-15	4 @ 20°C	37	32
Dukhan	41	-49	9 @ 15°C	36	33
Liverpool Bay	45	-21	4 @ 20°C	42	28
Sokol (Sakhalin)	37	-27	4 @ 20°C	45	21
Rio Negro	35	-5	23 @ 10°C	29	41
Umm Shaif	37	-24	10 @ 10°C	34	31
Zakum	40	-24	6 @ 10°C	36	33
Marine Gas oil (MGO)	37	-3	5 @ 15°C		

High pour point >5°C

	A	B	C	D	E
Amna	36	19	Semi-solid	25	30
Beatrice	38	18	32 @ 15°C	25	35
Bintulu	37	19	Semi-solid	24	34
Escravos	34	10	9 @ 15°C	35	15
Sarir	38	24	Semi-solid	24	39
Statfjord	40	6	7 @ 10°C	38	32

Note: High pour point oils only behave as Group 2 at ambient temperatures above their pour point. Below this treat as Group 4 oils.

Group 3 oils

A: *API 17.5–35 (Specific gravity 0.85–0.95)
B: Pour point °C
C: Viscosity @ 10–20°C: between 8 CSt and semi solid
D: % boiling below 200°C: between 10 and 35%
E: % boiling above 370°C: between 30 and 65%

Low pour point <6°C

	A	B	C	D	E
Alaska North Slope	28	-18	32 @ 15°C	32	41
Arabian Heavy	28	-40	55 @ 15°C	21	56
Arabian Medium	30	-21	25 @ 15°C	22	51
Arabian Light	33	-40	14 @ 15°C	25	45
Bonny Light	35	-11	25 @ 15°C	26	30
Iranian Heavy	31	-36	25 @ 15°C	24	48
Iranian Light	34	-32	15 @ 15°C	26	43
Khafji	28	-57	80 @ 15°C	21	55
Sirri	33	-12	18 @ 10°C	32	38
Thunder Horse	35	-27	10 @ 10°C	32	39
Tia Juana Light	32	-42	500 @ 15°C	24	45
Troll	33	-9	14 @ 10°C	24	35
IFO 180	18–20	10–30	1,500–3,000 @ 15°C		–

High pour point >5°C

	A	B	C	D	E
Cabinda	33	12	Semi-solid	18	56
Coco	32	21	Semi-solid	21	46
Gamba	31	23	Semi-solid	11	54
Mandji	30	9	70 @ 15°C	21	53
Minas	35	18	Semi-solid	15	58

Note: High pour point oils only behave as Group 3 at ambient temperatures above their pour point. Below this treat as Group 4 oils.

Group 4 oils

A: *API <17.5 (Specific gravity >0.95) or
B: Pour point >30°C
C: Viscosity @ 10–20°C: between 1500 CSt and semi-solid
D: % boiling below 200°C: less than 25%
E: % boiling above 370°C: greater than 30%

	A	B	C	D	E
Bachaquero 17	16	-29	5,000 @ 15°C	10	60
Boscan	10	15	Semi-solid	4	80
Cinta	33	43	Semi-solid	10	54
Handil	33	35	Semi-solid	23	33
Mersey	17	-21	7,000 @ 15°C	7	70
Nile Blend	34	33	Semi-solid	13	59
Pilon	14	-3	Semi-solid	2	92
Shengli	24	21	Semi-solid	9	70
Taching	31	35	Semi-solid	12	49
Tia Juana Pesado	12	-1	Semi-solid	3	78
Widuri	33	46	Semi-solid	7	70
IFO 380	11–15	10–30	5,000–30,000 @ 15°C		

Example oils classified according to their *API (American Petroleum Institute gravity). Indicative ranges of expected viscosities and distillation characteristics are provided for each group. Generally, when spilt, persistence increases with group number. However, if an oil cools to below its pour point temperature, it will change from a liquid to a semi-solid. This can occur for certain oils irrespective of whether they are classed as Group 2, 3 or 4. The pour points of oils classed as Group 1 are sufficiently low so as not to be a concern in the marine environment.

Source: ITOPF 2014/15 Handbook



Annex B – Vessel Traffic Patterns in Ice-Covered Waters

There is no straightforward way to compile or estimate the total number of winter voyages in ice in the different regions, Arctic or sub-Arctic. The coastguards' and Vessel Traffic Reporting systems of various nations maintain detailed data on every transit through their waters, but the data summaries generally lack any clear way of differentiating between an open water voyage and one in ice.

When considering marine traffic patterns in the Arctic, a distinction is often made between three basic traffic concepts, or sailing routes (Lloyds 2012):

- Intra-Arctic routes, i.e. sailing lanes between locations (ports) within the Arctic region. As an example, nickel shipments between the port of Kirkenes and the port of Murmansk.
- Destination-Arctic routes, i.e. sailing lanes from locations (ports) inside the Arctic region to destinations outside of the Arctic region. As an example, shipments from the port of Murmansk to the European markets.
- Transit routes, i.e. sailing lanes between ports in the Pacific and the Atlantic via the Arctic Ocean. As an example, shipments between ports in Germany and ports in China via the Northeast Passage through Russian waters (also referred to as the Northern Sea Route (NSR)) or Northwest Passage through Canadian waters (NWP). The cost and availability of adequate insurance is a continuing factor that ship owners must consider when deciding to use either the Northern Sea Route or the Canadian

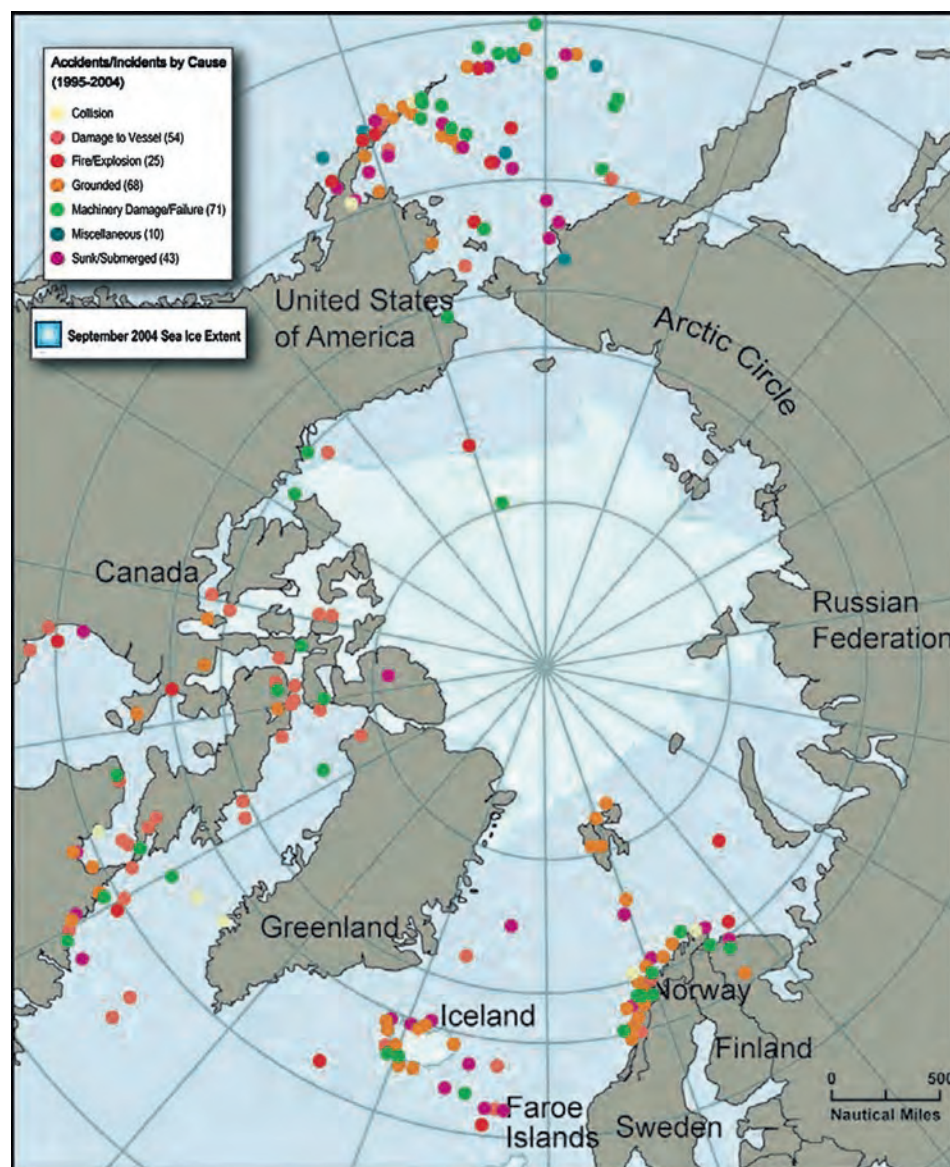
Northwest passage. As more experience is gained with commercial vessels on these routes, costs could come down.

Greater access to many areas as a result of longer summer open water seasons is expected to result in more frequent passages by commercial vessels and a higher risk of oil spills in the future. The Russian Northern Sea Route (NSR) is one example where this pattern is already leading to increased risk exposure in both Russian and US waters as large vessels (including tankers) pass laden southbound through the Bering Strait. It is important to place these Arctic trends in context, in order to judge potential spill risk. The actual number of these transits is still very small, particularly when compared to other international waterways – tens of voyages per year compared to for example, 15,000 for the Panama Canal (2008) and ~ 17,000 for the Suez Canal.

The original Arctic Marine Shipping Assessment, AMSA (Arctic Council, 2009), provides a comprehensive assessment of the geographic distribution and intensity of Arctic shipping (using data from 2004), and discusses the likelihood of continued expansion in numbers of vessels and voyages tied primarily to resource developments (mining, oil and gas) and tourism (FigureB.1).

AMSA demonstrates a clear connection between numbers of voyages and vessels in a given Arctic area and the frequency of damage incidents that could potentially result in pollution. Cruise ships were highlighted as one area of concern with the latest generation of vessels each carrying over 3,000 passengers

Figure B.1 Arctic ship-
ping accidents and
incidents causes,
1995-2004. Note that
most of these incidents
occurred during the open
water season when ves-
sel traffic in these areas
is most frequent (AMSA,
2009 Courtesy Lloyd's,
2012).



now venturing into Arctic and Antarctic waters. Apart from the very real issues associated with search and rescue and salvage, such large vessels pose a significant risk in terms of their bunker fuel volumes. As evidenced by the loss of the well-found MV *Explorer* in Antarctica in 2007, even ships with a long history of successful polar voyaging can experience a total loss event. This vessel also cruised in Arctic waters before this accident (Figure B.2).

AMSA provides a unique summary of vessel incidents and accidents in the Arctic over the decade 1994-2004. This dataset, although understandably limited by the still relatively small number of vessel movements, compared to other areas of the world, provides a basis for a broad analysis of the types of incident occurring in the Arctic and which areas may be more prone to incidents and, therefore,

potentially at greater risk to oil spills in the future.

The Norwegian Mapping Authority (2011) commissioned a study of marine traffic patterns throughout the Arctic. This report provides a more recent picture, compared to the baseline year of 2004 used in the AMSA, of the levels of commercial traffic and types of vessels involved. In recent years, international ship owners have increasingly focused on the possibilities of transit through the Russian Northern Sea Route (NSR). The current mix of vessels using the NSR includes specialised heavy-lift ships, petroleum product carriers, LNG tankers, iron ore bulk carriers, and oil and gas concentrate tankers. For example, during the five-month summer sailing season in 2011, nine large tankers with a total of 600,000 tons of gas condensate sailed the

Northern Sea Route: one of them a Suezmax super tanker 280 m in length and 162,000 Dwt. That volume was more than eight times more oil than was transported along that route during the previous year (T. Nilsen, 2011 <http://barentsobserver.com/en/security/less-russian-oil-around-coast-norway>).

The Arctic Institute released a more recent report (“Arctic Shipping: An Analysis of the 2013 Northern Sea Route Season”), which analyses data collated by the Northern Sea Route Information Office. Over the course of 154 days that year, a total of 49 vessels transported 1.35 million tons of cargo including a mix of petroleum liquids and crude oil. A further 22 vessels transited the NSR unladen (in ballast). The Northern Sea Route Information Office lists a total of 71 transits for 2013 but a closer analysis of the data shows that:

- Only 41 vessels travelled the entire length of the NSR and qualify as full transits;
- An additional 23 vessels either departed from or arrived at ports inside the NSR and did not fully complete a transit; and
- A further 7 vessels travelled exclusively within the NSR.

Only 30 of the 41 ships that completed the full transit carried cargo. The report concludes that the NSR remains a niche trade route with limited numbers of true transits. The export of Arctic hydrocarbon resources, primarily from Russia, and their transport along the NSR can be expected to grow over the coming years. However, this will not establish the NSR as a true trade route but, in contrast, place even greater emphasis on one-directional traffic from west to east (<http://www.thearcticinstitute.org/>).

It should be emphasised that most of the commercial vessel traffic with ice-strengthened, as opposed to true icebreaking hulls, in Arctic waters occurs in ice-free or nearly ice-free conditions. Notable exceptions include specialised shuttle tankers loading at the Varandey offshore loading terminal in the Pechora Sea, tankers exporting oil from the Prirazomloye offshore production platform also in the Pechora Sea, icebreaking ore carriers serving the Norilsk nickel mines in Siberia, icebreaking bulk carriers serving mines in



Labrador and Northern Quebec, and low-ice class tankers exporting Sakhalin oil from the De Katri terminal.

Figure B.2 *MV Explorer, expedition cruise ship sinking in ice off the South Shetlands (2007).*

In a new development in the planning stages for some years, Gazprom Neft is planning to build a major oil transshipment terminal western shore of Ob Bay to support the Novoportovskoye field. The goal is to ship the oil out through the Northern Sea route on a year round basis. Phase I is scheduled to commence late 2015. When fully operational (expected by 2019), the terminal will ship some 8.5 million tonnes of oil per year. The port will be able to accept ice class tankers (Arc6) with deadweight of up to 55,000 tonnes, draught of up to 9 m and maximum width of 32-34 m. The tankers will perform round the year shuttle voyages to deliver crude oil to Murmansk (Belokamenka terminal) for further transshipment to Aframax tankers and transportation to Rotterdam (Source: Barents Observer).

To date there have been only a small number of experimental winter voyages into the Ob Bay area. The most significant of these involved the Finnish-built icebreaking tanker *Uikku* supported by several Russian icebreakers in May 1998. The voyage and data collection was sponsored the European Commission as part of the ARCDEV project (see references for final report).

Figure B.3 shows one of the Russian river icebreakers specially designed to assist commercial vessels in ports and shallow shipping



Figure B.3 Russian nuclear-powered river icebreaker *Taymyr* escorting product tanker *Indiga* near the port of Dudinka Photo: Timur V. Voronkov. Licensed under Creative Commons Attribution- Wikipedia.

lanes in areas like the Yenisei River and Ob Bay.

Over the past decade, the number of tankers transiting along the Arctic coast of Norway from Vardø to Røst increased from 160 in 2002 to 278 in 2010. This shipping route is in open water year-round but the consequences of a worst-case incident would be considerable. This increase in the level of traffic is worth noting as the route is in Arctic waters and serves as an example of the type of risk that could increase in other areas with ice if Northern Sea Route (NSR) tanker and other commercial traffic with a potential to encounter ice along the voyage, continue to expand.

In contrast to the Russian sector or Norwegian North coast, the Canadian Arctic still has far fewer commercial voyages during the average summer navigation season (July to October). Most of these voyages occur in open water. The majority of large ships engaged in trading in Canadian Arctic waters are lightly ice-strengthened bulkers serving Churchill in Hudson Bay (outside the study area of this guide) through Davis Strait in the summer, and specialised ice-breaking bulk carriers

serving year-round mine sites in Deception Bay, Quebec and Voisey's Bay, Labrador (also outside the study area).

Unlike the NSR, there are no established deep-draft ports through the Northwest Passage (NWP) and along the Alaskan coast. Obstacles to expanded use of the NWP by large vessels include draft restrictions, unpredictable summer ice conditions, navigation challenges, inadequate charting, and the costs and availability of insurance.

Arctic cruise traffic falls into two categories: ecotourism using a small number of chartered Russian icebreakers which are capable of transits through severe ice conditions and/or specialised expedition cruise ships capable of limited ice operations and carrying up to hundreds of passengers; and a larger number of non-ice strengthened cruise ships capable of carrying thousands of passengers. These very large vessels are limited to open water operations and make every effort to avoid direct ice contact. There is still considerable uncertainty about future trends in cruise vessel traffic in Arctic waters. For example, new figures from the Association of Arctic Expedition Cruise

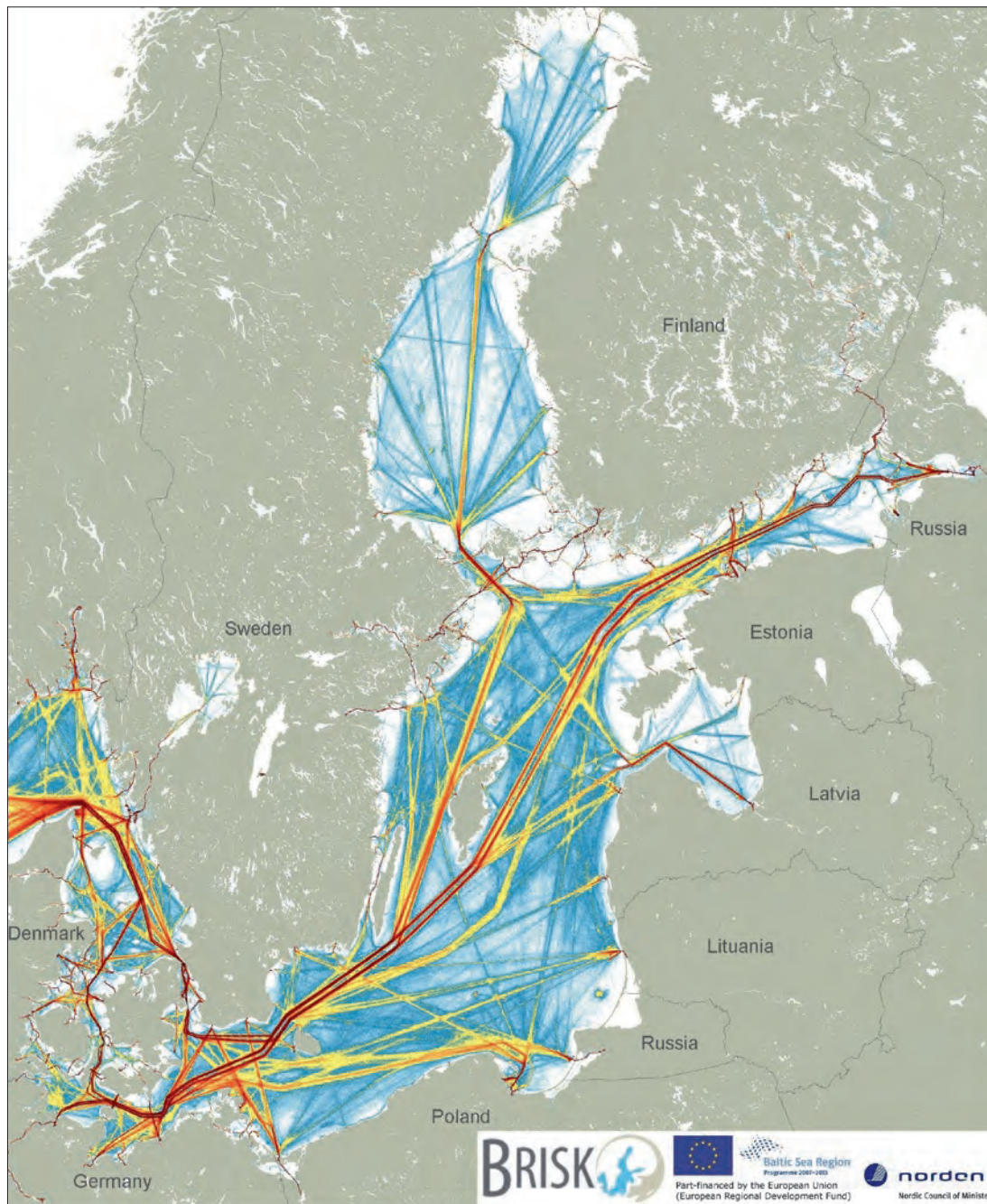


Figure B.4 Ship traffic intensity in the Baltic Sea 2008-2009, red being the areas of highest traffic frequency (Source: http://www.brisk.helcom.fi/risk_analysis/traffic/en_GB/traffic/).

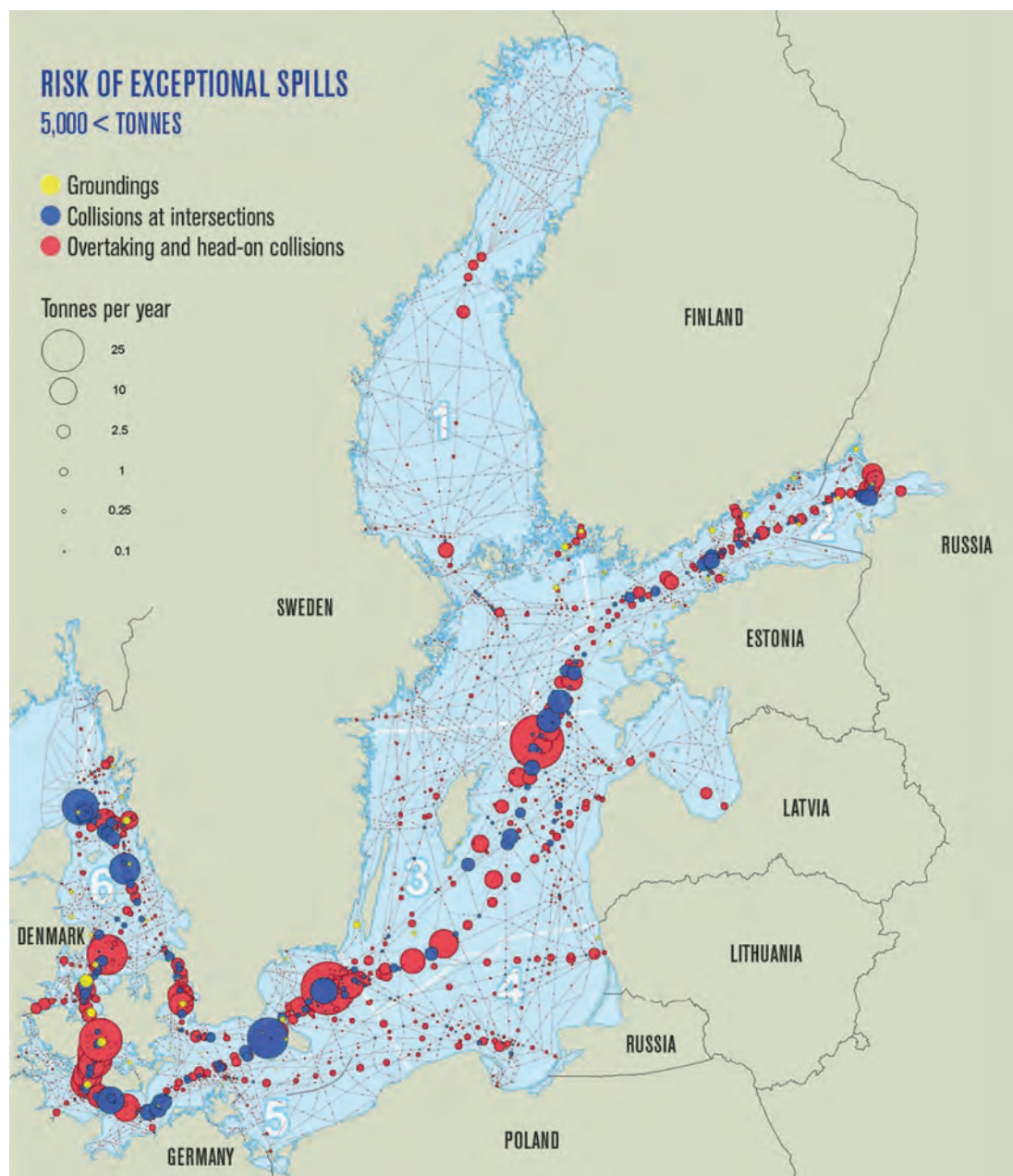
Operators, AECO, point to a significant decline in cruise passengers since 2010: information presented at a meeting in Ottawa in March 2014 organised by Arctic Council's Protection of the Arctic Marine Environment (PAME).

Sub-Arctic Shipping Activities in Ice

There are two sub-Arctic areas important for winter shipping and falling within the study area covered by this guide:

1. Baltic Sea with the highest intensity of commercial winter vessel traffic in the world (general cargo vessels, bulk carriers, tankers, ferries etc.). Much of the recent increase of traffic in this area is related to expanded Russian terminals.
2. Sea of Okhotsk including:
 - a. North Sea of Okhotsk, with a range of vessels serving Russian ports such as Vladivostok.
 - b. Japanese Sea of Okhotsk and north of Hokkaido.

Figure B.5 Annual cumulative risk of spills over 5,000 tonnes, separated according to accident type and location (Source: http://www.brisk.helcom.fi/risk_analysis/spills/en_GB/spills/).



- c. Sakhalin Island, with oil producing platforms and pipelines in severe, rapidly moving pack ice off the East Coast as well as major tanker terminals for oil and LNG at De Kastri, respectively on the Russian mainland and at Aniva Bay on the south shore of Sakhalin Island, which typically have ice for several months every year.

A significant difference between these two sub-Arctic areas concerns the structure and type of ice. In the case of Sakhalin Island, the ice is true sea ice formed from normal salinity seawater. In contrast, Baltic ice is formed from brackish water ranging from low salinity

to nearly fresh. This has implications in terms of expected oil behaviour in ice, notably the timing and likelihood of oil migration to the ice surface during early melt period as well as the potential for different remote sensing instruments to penetrate the ice cover and detect oil trapped beneath or within. Refer to associated discussions in Chapters IV-1e and V-2a in the main report.

In terms of numbers of transits through ice and the associated risk of accidental spills, the frequency of regular winter shipping in the Baltic Sea, notably in the Gulf of Bothnia and Gulf of Finland, completely dwarfs the relatively small number of winter voyages occurring in the Canadian and Russian Arc-

tic (Figure B.4). Around 2,000 sizeable ships are normally at sea in the Baltic at any given moment. Source: http://www.brisk.helcom.fi/risk_analysis/traffic/en_GB/traffic/

The Gulf of Finland stands out as an area where the marine transport of oil cargoes in ice has increased dramatically over the past decade. There are 17 oil ports in the Gulf of Finland, of which six are in Finland, six in Estonia and five in Russia. Oil transportation in this region has almost quadrupled in the past ten years. In 2000, slightly over 43 million tonnes of oil and oil products were transported and handled in the Gulf of Finland. In 2009, this figure was 150.6 million tonnes and, in 2010, almost 160 million tonnes (Brunila and Storgård, 2013).

Figure B.5 shows the distribution of spill risk related to the predicted frequency of different types of vessel accidents along shipping routes throughout the Baltic. The same HELCOM data source also contains spill risk maps for spills <300 tonnes and between 300 and 500 tonnes.

The risks can also be expressed as the expected intervals between spills of a specific size range, for the whole Baltic Sea or in different sub-regions. A spill in a range of 5,000 tonnes and above could occur once every 26 years, while a spill in a range of 300-5,000 tonnes is expected to occur as frequently as once every 4 years somewhere in the Baltic, not necessarily in ice. The biggest risk areas are the south-western Baltic and the Kattegat.



Annex C – Trends in Oil and Gas Activities in Ice-Covered Waters

At first glance, this map appears to show a high level of oil and gas exploration activity in the Arctic; the reality at time of writing (2014) is quite different. Major companies involved in US Arctic offshore exploration activities have put their plans on hold pending government clarification of drilling and contingency plan requirements or are awaiting the results of pending litigation by opponents of Arctic drilling. Deep water leases in the Canadian Beaufort Sea are being evaluated and

assessed by the operators, with one application in process to possibly commence exploration in 2020 or later.

After considerable activity off West Greenland in the past several years, no companies filed to drill in 2014. Recent leases granted off the Northeast Coast of Greenland are unlikely to see exploration until beyond 2020, owing to the challenging ice conditions, limited to non-existent open water season in many years and extremely high per-well cost. Seismic sur-



Figure C.1 Arctic oil and gas provinces and basins showing existing and proposed production (Sources: AMAP, 2008; Updated by Anderson, 2010).

Figure C.2 *Stena Drillmax Ice, an example of a modern Arctic, ice class drillship (Illustration: Stena).*



veys and research cruises are the most likely marine operations to be sponsored by the oil industry in this region for the foreseeable future.

The Kara Sea exploration program launched by the ExxonMobil/Rosneft joint venture came close to being suspended by US sanctions but ExxonMobil was granted an exemption to October 10 in order to complete drilling. The Karmorneftegas drilling program (University-1 site) was one the “most remote” undertaken to date – for example, the 850 nm

transit distance to the nearest logistics base (Murmansk) is well beyond helicopter range. The same joint venture launched a new 2D seismic program in the summer of 2014 offshore in the Laptev Sea, but the future of this work is uncertain at present. Recent indications are that Russia intends to actively continue oil exploration throughout the Arctic. Source: http://www.nytimes.com/2014/10/30/business/energy-environment/russia-oil-exploration-sanctions.html?_r=4

On September 29, 2014, Russia’s Rosneft



Figure C.3 *Orlan oil production platform offshore Sakhalin Island (Source: ExxonMobil).*



Figure C.4 Single point mooring with Tanker loading oil from Sakhalin 1 at the De Kastri terminal.

announced a major oil and gas discovery in the Arctic Kara Sea following the drilling of the northern-most well in the world in the East-Prinovozemelsky 1 block, which it explored together with ExxonMobil. “According to preliminary results, the resource base of the first hydrocarbons trap discovered through the drilling is estimated to hold 338 billion cubic metres of gas and over 100 million mt (730 million barrels) of crude,” Rosneft’s CEO Igor Sechin said in a statement.
Source: <http://www.platts.com/latest-news/oil/moscow/russian-rosneft-announces-major-oil-gas-discovery-21300064>

Drilling in the Norwegian Barents Sea continues to move further north, as far as 74°N, 350 km north of Hammerfest, with Statoil’s recent 2014 campaign. On October 14 of that year, The Norwegian Petroleum Directorate headlined a significant new discovery by LundinOil at the Alta prospect north of 72 degrees in the Norwegian sector of the Barents Sea. The company estimates the discovery at 85 to 310 million barrels of oil, or some 14 to 50 million standard cubic metres. Together with Statoil’s Johan Castberg field, this is the northernmost significant oil discovery in the Norwegian Arctic to date. Both Norwegian



Figure C.5 Pirazomloye offshore oil production platform in the Pechora Sea, Russia - first oil by tanker April 2014 (Source: offshoreenergytoday.com).

Figure C.6 *Northstar oil production island in shallow water (12 m) off Prudhoe Bay (Photo: Lori Murray).*



discoveries are south of the seasonal ice edge.

Source: <http://barentsobserver.com/en/energy/2014/10/significant-barents-sea-oil-discovery-14-10>

The giant Shtokman gas field development in the North Russian Barents Sea now (2014) appears to be on indefinite hold. The shareholders agreement expired June 2012 with no development started.

As with shipping, there is an equal or greater risk of spills into ice covered waters originating from drilling activities in sub-Arctic areas, for example:

- Cook Inlet, which has produced over 1.3 million barrels of oil safely since the late 1960's in highly dynamic ice (outside the scope of this Guide). Over 240 exploration oil wells were drilled in Cook Inlet over the past 60 years
- Sakhalin 1 and 2, oil and gas production (currently expanding with plans for Sakhalin 3 development in the future).

The figures below show examples of a number of Arctic drilling rigs, production facilities and tanker loading terminals in the US and Russian Arctic and Sakhalin Island, Russia.

Although at a low level compared with other world oil producing regions, as of 2010 there were four oil platforms in the Baltic Sea, all of them located in the south-eastern part of the region in the oil fields of Kravtsovskoye and B-3. Three of the platforms, Baltic Beta, Petro Baltic and PG-1, are Polish, and one, MLSP D-6, is Russian (Source: WWF, 2010).

Annex D – Ice Cycles

- The ice cycle refers to the history of an ice sheet or an ice formation from freeze-up to break-up or melting.
- The timing of a spill in relation to this cycle and the associated ice character directly affect many of the interactions and processes that control the oil behaviour and possible response options.

The following subsections describe the different ice cycles affecting the formation, growth and decay of:

- Offshore Drifting Sea Ice
- Seasonal Shore Zone and Nearshore Ice
- River Ice
- Terrestrial Ice and Snow

Sea Ice Cycle

When sea ice first forms on the ocean surface in the fall, there is a transition through a range of stages described in more detail below that depends on atmospheric and ocean conditions. This growth process yields first-year ice, which in a single season may reach a thickness of 1.5-2 m, for example, in the Chukchi, Beaufort and Kara Seas. In more temperate areas, such as the Barents Sea, Baltic Sea and offshore Sakhalin, maximum winter level thicknesses are typically in the range 80 cm to 1 metre. The following sections review the different periods within the “Ice Cycle” focusing on the Arctic Ocean.

Some key differences are pointed out with respect to Baltic ice in comparison to sea ice at higher latitudes.

Freeze-up and Winter Growth

The fall transition from the first appearance of new ice to almost complete ice cover (8/10 or more) near shore occurs rapidly in most Arctic areas, often within a week or less. Initial ice growth along the coast can reach 30 cm within two weeks after the first occurrence of new ice, often as early as late September. The first sea ice to form on the surface is a skim of separate, random-shaped crystals which form a suspension of increasing density in the surface water: an ice type called frazil or grease ice (thin layers of clumped crystals on the ocean surface that can resemble an oil slick from the bridge of a vessel) (photo A in Figure III-2.9).

These initial ice forms can also include slush ice formed when snow falls at the same time. Shuga is formed in agitated conditions by accumulations of slush or grease ice into spongy pieces several inches in size. The slush between thicker floes significantly restricts oil spreading in leads, maintaining oil in patches thick enough for ignition and effective in situ burning (Buist and Dickins, 1987) (Figures IV-1.3 and IV-1.4).

With any significant wave action, the frazil crystals can accumulate into slushy circular disks, called pancakes or pancake ice, due to their shape. A signature feature of pancake ice is raised edges or ridges on the perimeter, caused by the pancakes bumping into each other from the ocean waves. In time, the

Figure D.1 Pancake ice (foreground) within pack ice off Nova Scotia, Canada (Photo: D. Dickins).



pancake ice plates may themselves be rafted over one another or frozen together into a more solid ice cover, having a very rough appearance on top and bottom. Pancake ice is common near an ice edge where wave action from the open sea penetrates the pack and jostles the new ice cakes together. Examples where this type of ice is common would be the southern Bering Sea, Davis Strait, and the Norwegian Barents Sea.

In quiet conditions with no wind or waves, the frazil crystals soon freeze together to form a continuous thin sheet of young ice, called nilas. When only a few centimetres thick this is transparent (dark nilas), but as the ice grows thicker the nilas takes on a grey and finally a white appearance.

A small proportion of the salt in the parent seawater (10 to 20%) is trapped as highly concentrated brine in closed cells between the ice crystals. As the sheet gradually warms in late winter, most of this brine drains out of the bottom of the ice, leaving pathways to the surface for oil migration (Chapter IV-1e: Figures IV-1.7 and IV-1.8 in the discussion on oil behaviour in ice in the main report.

Ice Roughness

The type and severity of ice roughness has major implications for detecting, mapping

and accessing oil trapped beneath the ice, for surface travel, and for other logistics challenges such as landing helicopters or fixed wing aircraft.

Level ice thickness values are somewhat academic in terms of planning spill response and only apply in any great extent to smoother fast ice close to shore in water depths less than ~10-12 m. In reality, much of the offshore ice cover is deformed through crushing and shearing, forming ridges and rubble, or by young ice rafting over itself in the first few months following freeze-up. These processes create patches of ice made up of multiple thin sheets adding up to several metres or more of total thickness, even in sub-Arctic areas. Ridges have keels that can extend over 30 m below the surface, composed of many partially bonded randomly oriented blocks and void spaces with sails rising 5 m or more above the surrounding ice field. The deepest ridge keel documented in the Beaufort Sea region over the past 20 years had a draft of 37 m (Melling and Riedel, 2004).

Rubble ice, by comparison, is a jumble of ice fragments that cover a larger expanse, tens of hectares, without any apparent linear patterns. Figure D.2 shows extensive moderate to severe rubble in the Chukchi Sea.

Even smooth, level ice areas show distinct natural variations in thickness, expressed as



Figure D.2 View of typical offshore rubble and ridging viewed from a USCG Polar class icebreaker in the Chukchi Sea, April (Source: Arctec).

undulations or troughs in the underside of the sheet. The spatial variation in snow cover on the ice surface plays a key role in controlling the orientation, spacing and shape of these natural under ice depressions. Areas of thinner ice correspond generally to surface areas with thicker snow. The average snow cover on sea ice tends to be quite thin, reflecting the Arctic desert climate but in some areas, such as coastal Labrador and in the lee, or flanks, of ridges, a heavy enough snow cover can build up sufficiently to depress and flood the sea ice.

This natural variability in ice sheet roughness creates reservoirs where large volumes (tens of thousands barrels) of oil, can remain trapped under the ice through the winter and contained in relatively small areas (Wilkinson *et al.* 2007).

The Summer Melt Period

In most Arctic areas, the overlying snow layer typically begins to melt in late May and is gone by early June. Melt water from the snow creates a network of meltwater pools over the ice surface. In first-year ice, oil trapped under or encapsulated within the ice migrates to the surface through channels left in the ice as the heavier brine drains out. Once on the ice surface, winds herd the oil into thicker patches on the lee side of melt pools that can then be effectively ignited and burned, often with high efficiencies depending on pool size and oil thickness (Norcor, 1975; Dickins and Buist 1981; Brandvik *et al.*, 2006) (Figure IV-1.7).

On first year ice, melt pools are initially

very shallow, forming in minor depressions in the ice surface, or simply being retained initially within surviving snow pack as a layer of slush. Over several weeks, the pools melt their way down into the ice through preferential absorption of solar radiation by the water. Other discontinuities such as cracks and seal holes expand through the same process and become connected pathways for vigorous drainage of the surface water. In near shore fast ice areas, this process of *strudel* drainage can be quite violent and create large scoured pits in the seabed. It has been postulated that this drainage process could redistribute surface oil beneath the ice (Dickins and Owens, 2002). Refer to the following discussion of the related river over flood phenomenon.

Differences in Baltic Ice Cover Formation and Composition

Granskog *et al.* (2006) discuss the physical structure of Baltic ice and point out the following key differences that distinguish brackish ice formed in this area from sea at higher latitudes in the Arctic Ocean.

- Airborne surveys with electromagnetic (EM) towed “birds” show that there is a greater amount of deformed ice in the Baltic with mean thickness > 1 m than shown in routine ice charts (Haas, 2004). Consequently, the total ice volume in the Baltic may be larger than previously thought.
- Baltic ice is greatly affected by frequent freeze-thaw cycles that can occur during

the winter. Consequently, ice growth is far from continuous from freeze-up to break-up.

- The level landfast ice (out to ~ 5-15 m water depth) is divided into a two layer structure with a granular upper layer composed of snow ice or superimposed ice, and a columnar (aligned crystal axes similar to sea ice) bottom layer.
- Snow ice contribution to overall ice thickness is far greater in the Baltic than the high Arctic – for example studies have shown that this type of ice can make-up almost half the land-fast cover whereas the contribution of snow ice to landfast sea ice growth in the high Arctic is negligible. Areas like the Sea of Okhotsk tend to fall somewhere between the Arctic and Baltic in terms of snow ice mass percentage. *Note: snow ice is common in areas with sufficient snowfall to submerge and flood ice sheets early in the season. This water along with the saturated snow subsequently freezes and can make up a substantial part of the overall ice mass. Snow ice is not common in the Arctic because the climate is close to desert like in terms of precipitation. More southerly areas like the Sea of Okhotsk, Labrador, and the Baltic commonly see much thicker snow build-up on the ice.*

Seasonal Shore zone and Nearshore Ice Cycles

- The shore zone ice and snow cycles are controlled by local air temperatures.
- At the regional scale, the significance of ice in the coastal zone increases as temperatures decrease and the length of the winter season increases.
- The local shore-zone ice character and the seasonal cycle control oil behaviour and response options.

Snow and ice can form on any shore line when air temperatures fall below freezing. In most regions the presence of snow and ice in the shore and nearshore zones is directly related to the seasonal air temperature cycle, and the significance of snow and ice with respect to oil spill response increases as temperatures decrease and the length of the winter season increases. Water depth is a factor in the nearshore ice cycle as ice typically persists longer and clears more slowly in shallow waters, thereby prolonging the period during which ice is a factor in oil behaviour and response strategies.

Shore zone and nearshore ice should be viewed at two scales: at the regional level the presence or absence of ice on coastal waters

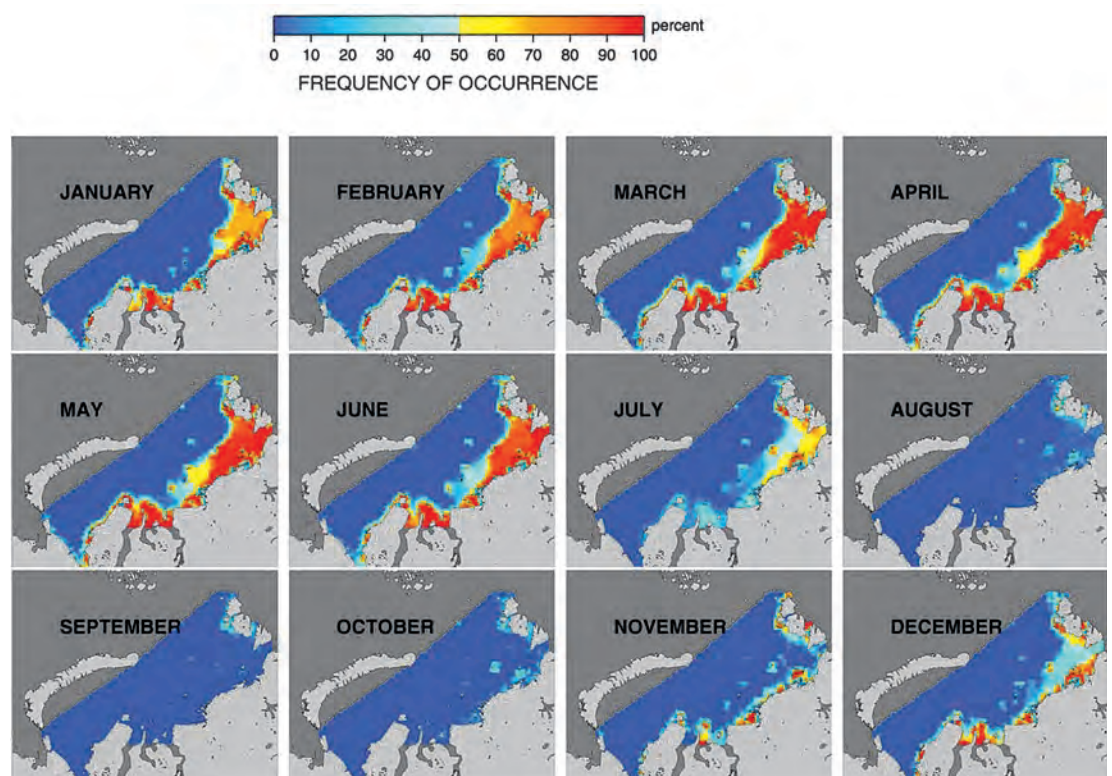


Figure D.3 Monthly probability of shore fast ice in the Kara Sea (Divine et al. 2004). *NOTE: This figure only shows shore-fast ice. Offshore ice is present typically in the mid Kara Sea from October to July. The blue colour is not indicative of open water and only refers to a zero probability of encountering shore fast ice in the Kara Sea far from shore.*

SEASON	SHORE ZONE	NEARSHORE
ICE FORMATION PERIOD – Early winter	First Snow First Shore zone ice: freeze and thaw of wash spray and swash	Open water: first ice, some frazil, slush or pancake ice forms
	Increasing thickness of shore zone snow and ice	Increasing thickness of ice with potential disruption by storms: initial land-fast or shore-fast ice
STABLE ICE PERIOD – Winter	Stable snow and ice	Stable ice cover with land-fast ice
TRANSITION PERIOD – Early Spring	First snow melt River discharge begins	Stable ice with surface melting and overflowing at river mouths
MELT PERIOD – Spring/Early Summer	Snow cover melts Peak river discharge levels Shore zone ice deteriorates	Breakup and ice clearing
ICE FREE – Summer	Snow and ice free	Open water: ice free

Table D.1 Seasonality of Shore Zone Ice and Snow.

controls the local wave climate, whereas locally the character and roughness of the ice (see discussion above) and the shore-zone ice cycle control oil behaviour and response options. The eastern area of the Kara Sea provides an example of regional variability and the seasonal character of coastal ice (Fig. D.3). The western part of the Southern Kara Sea remains largely ice free year-round, whereas east of the Yamal Peninsula the ice season in

all coastal waters is November through July. However, even in areas with an almost ice-free coastal environment, intertidal ice forms locally due to below freezing air temperatures – see further discussion below.

Freeze Up and Winter Growth

The initial period during which snow falls and ice forms may involve multiple freeze-thaw



Figure D.4 The winter beach cycle:

- A.** initial freezing of swash and ice foot formation with back-shore snow accumulation
- B.** formation of continuous shore fast ice seaward of the intertidal zone (ice foot)
- C.** stable shore-zone and nearshore ice cover
- D.** breakup/removal of nearshore ice; snow melt and deterioration of the shore zone ice.

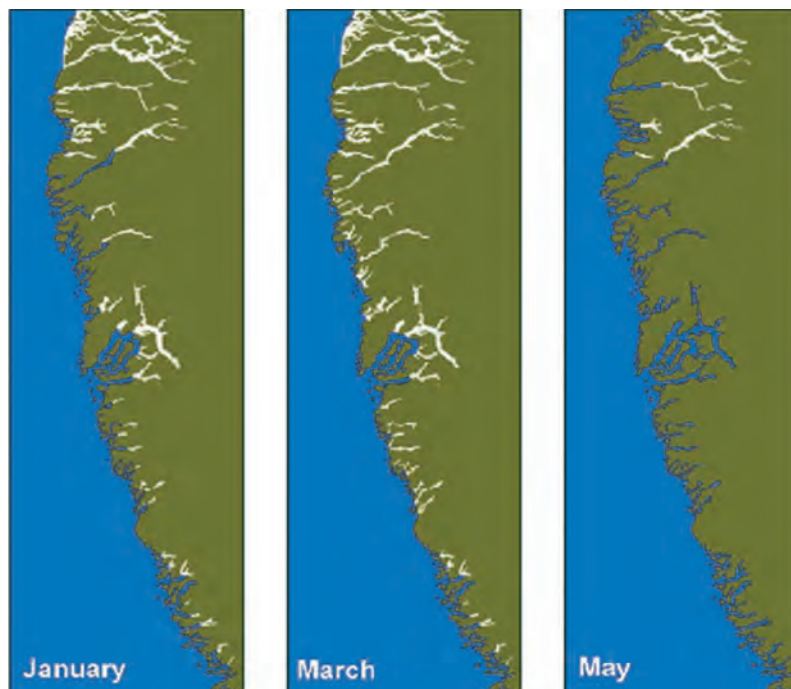


Figure D.5 Ice-covered shorelines on the West Coast of Greenland: January-May (Stjemholm et al. 2011).

cycles, even on a daily basis, as air temperatures oscillate around the freezing point. Typically, seasonal shore ice begins to form before nearshore ice and persists after the nearshore ice has broken or melted, thus shortening the period when shorelines are ice free.

The presence of an ice layer on the shoreline substrate (Figure D.4 A, B, C) prevents contact by oil. Any oil at the shoreline during this period may then be redistributed on the open waters or frozen in new growth ice. Table D.1 summarises the seasonality of shore zone ice and snow.

The presence of shore zone (intertidal) or shore-fast (nearshore) is highly variable in time and space. Along the west coast of Greenland the northern coasts may be ice-free for only a few weeks or months each year, whereas

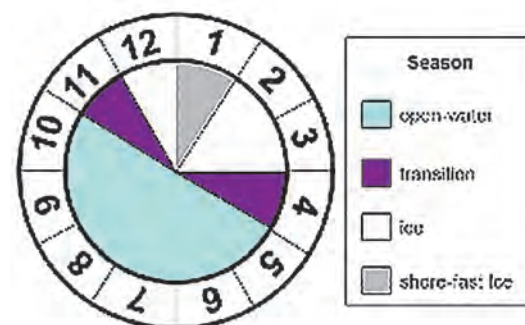


Figure D.6A Annual coastal ice cycle, Northeast Sakhalin Island.

to the south the outer coasts and nearshore waters may be ice free all year. Superimposed on this regional scale trend in Greenland, shorelines in sheltered bays and fjords may be ice-bound for 6 months or more at times when the open coast is ice-free (Figure D.5).

The Spring/Summer Melt Season

Within the general seasonal trends (Figure D.4), the dates of break-up and freeze-up at any one location can vary from year to year over a range of up to several weeks. With warmer air temperatures, snow melts and the intertidal shore zone ice thaws and deteriorates in place (Figure D.4D).

Data from Northeast Sakhalin Island provide an example of a typical shore zone and coastal ice cycle (Figure D.6A). Shore-zone Ice is a factor for half of each year. The timing of strongest onshore winds coincident with open water, and therefore the period with potentially the highest locally-generated waves, is limited to the autumn (September to early November). This coast has a mobile offshore

	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
onshore average wind speed >4 m/s												
offshore winds >10 m/s		?										
coastal ice												
fog												
wave height >1.25 m (50%)		?		?								
air temperature <0 °C												

Figure D.6B Annual cycle of shore-zone processes, Northeast Sakhalin Island.

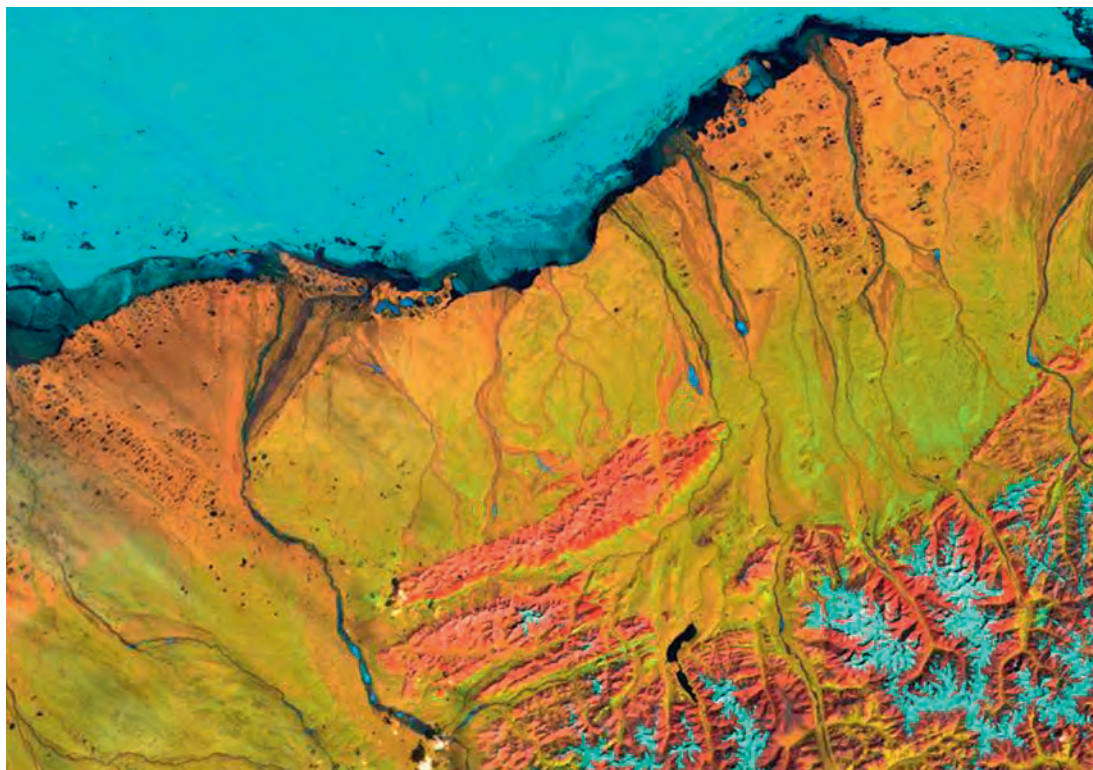


Figure D.7A North Slope, Alaska: July 6 2000. A scenario with a narrow open coastal lead between the sea ice and the shoreline which acts as a corridor within which spilled oil would be contained (Source: USGS Landsat 7).

ice field with land-fast ice at the shoreline (Figures III-3.2E and D.6A and B). At the end of the winter cycle the shore zone frequently is characterised by a mixture of beach sediments, a deteriorating ice foot and grounded ice floes (Figure III-3.4A).

On open coasts with a narrow shallow shelf (e.g. the Alaskan Chukchi Sea) the land fast ice may clear rapidly due to wind and/or currents. In areas such as the Alaskan North Slope, the land fast ice stretches tens of kilometres from shore in water depths less than 20 metres and clears relatively slowly. In this

case, the first areas to open are immediately adjacent to the shore where a narrow open-water corridor in very shallow water is created by relatively warm water flowing out of the coastal rivers and rotting the nearshore ice (Figure D.7A). This open coastal lead between the sea ice and the shoreline can act as a corridor within which spilled oil, or oil spilled earlier and released by the melting of snow and ice, would be contained at a time of relatively calm wave conditions.

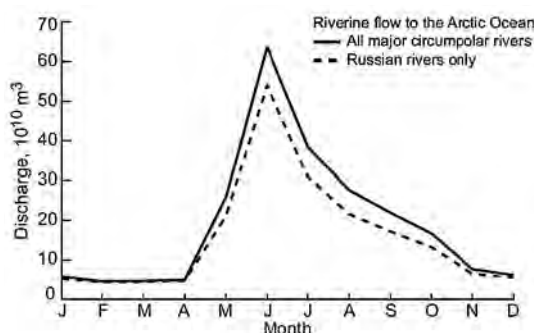


Figure D.7B North Slope, Alaska: August 30 2000. Same location as D.6A with an almost ice-free coastal environment (Source: USGS Landsat 7).

River Ice Cycle

- Coastal rivers in regions with ice and snow typically have low winter discharge followed by high flow and flooding during the spring melt and breakup period.
- Channels typically contain ice floes during the breakup period.
- River discharge overflows land-fast coastal ice where it is present during the high flow stage, sometimes for many kilometres. These waters may drain under the ice through cracks or seal holes.

Figure D.8 Mean seasonal variation of river discharge into the Arctic Ocean (from Fisher et al. 2012).



River cycles in cold climates follow a distinct seasonal pattern (Figure D.8), and the magnitude of the seasonal variation is primarily a function of the size of the drainage basin. This figure also clearly shows how Russian rivers dominate the total discharge of freshwater into the Arctic Ocean. During winter months rivers typically are in a low flow stage due to cold interior temperatures that cause precipitation to fall as snow. Small rivers may be dry and larger ones flow at low discharges to the

Figure D.9 Break up on the Colville River, Alaska (Photo: ConocoPhillips).



sea underneath the ice, as is the case with the Colville on the Alaskan North Slope.

River water levels begin to rise rapidly in early spring as increasingly warmer air temperatures melt inland snow accumulations. Discharge into coastal waters can be limited by ice jams in the lower reaches of a river (Figure D.9) or by the presence of ice that frequently is frozen to the nearshore sea bed. The rising river waters flood adjacent low-lying areas and flood over the nearshore ice. Large rivers with deltas, such as the Yukon and Colville Rivers in Alaska, the Mackenzie River in Canada, and the Lena, Ob, Yenisei, and Amur Rivers in Russia experience wide scale flooding typically accompanied by the presence of strong currents and broken ice. Overflowing on the coastal ice can extend many kilometres seaward (Figures D.10 A and B) and water can drain through ice cracks or seal holes to create *strudel* holes that can resemble violent whirlpools (Figure D.10C). An oil spill at this time of year into a river would result in the rapid distribution of oil both onto the low-lying flood plains and potentially over and under the nearshore ice at a time when safety concerns and feasibility would largely preclude a response operation.

Terrestrial Ice and Snow Cycles

- On land, ice may be present “year round”, as permafrost. This ice may be exposed at the coast or may underlay low-lying tundra.
- Seasonal ground ice forms in the “active” zone above the permafrost or in beach and riverbank sediments where the water table is near the surface.
- Snow is common when air temperatures drop below freezing. This can accumulate and can form ice during freeze-thaw cycles.
- The high latitude coasts have desert climates so that the total annual precipitation typically is less than 20 cm of equivalent water.

Terrestrial ice may be present either year-round or seasonally. Permafrost (or “ground

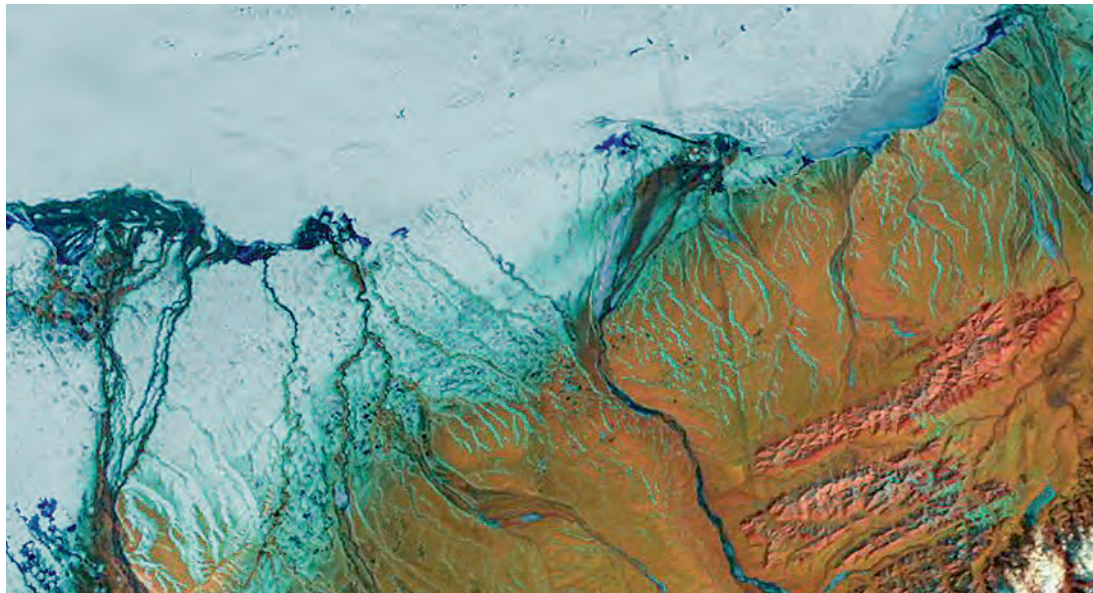


Figure D.10A Coastal overflow in an advanced stage on the Alaskan North Slope (13 June 1986). Prudhoe Bay is close to open water at the far left (West) of the image, with the Sagavanirktok Delta overflowing (Endicott production island) immediately to the east. The offshore sea ice is still 8/10+ concentration in the early stages of break-up (Source: Landsat 7).

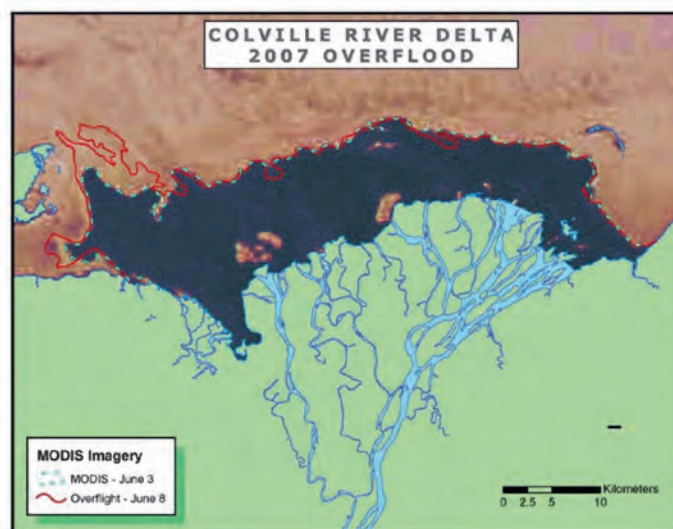


Figure D.10B Colville River 2007 overflow limit (red Line) mapped with MODIS imagery. The tan colour represents sea ice and the dark is the area with surface water on the sea ice (Hearon et al. 2009).

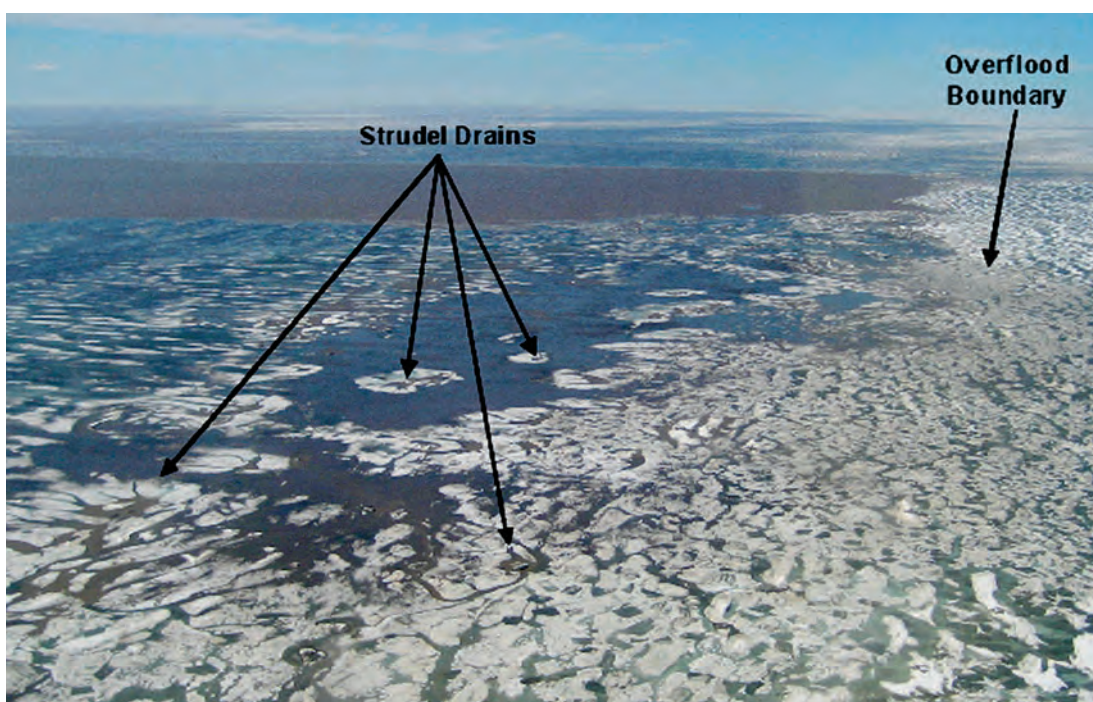


Figure D.10C Examples of "strudel drainage" within the Colville River overflow area (2007) (Hearon et al. 2009).

ice”) in the coastal zone is found in Siberia, Alaska, northern Canada, Greenland and Antarctica and is soil or sediment that remains frozen throughout the year (Chapter III-2: Figures III-2.14 and 2.15). The thin surface, or “active” layer, may thaw and melt with seasonal changes in air temperature and may support plant life.

Seasonal ice forms by the freezing of interstitial waters on land or in beach and riverbank sediments where the water table is near the surface. This ice fills the void spaces between sediments to act as an impermeable layer that limits the penetration of oil deposited on a shoreline or river bank.

Snow falls and accumulates when near-ground air temperatures remain below freezing. The surface of fresh snow is characterised by a loose aggregation of individual crystals which, if the snow continues to accumulate, become compacted and denser as the weight of the overlying snow layer increases. This change creates a more tightly packed structure as air spaces are eliminated and porosity decreases. Eventually the snow may recrystallise into firm, or “old” winter snow. Clear blue ice will form if almost all of the air is expelled, a condition which typically requires accumulations in the order of 50 m or more.

Under quiescent environmental conditions, snow can accumulate with a simple vertical variation in density and porosity. In most situations, however, this steady accumulation is interrupted by the effects of freeze-thaw cycles and wind. Diurnal temperature oscillations around the freezing point are a common

feature during the freeze-up period. These alternate ablation and freezing processes can generate ice layers as snow melts during daylight warm temperatures and freezes at night when temperatures drop below zero. If this freeze-thaw cycle is accompanied by precipitation, a range of features can form that may include alternate layers of snow and ice. Wind action can strip the loose surface crystals to expose more dense lower snow layers, and the blown, powdery snow can accumulate in hollows, depressions, or wind shadows.

Most coastal zones in the northern hemisphere have summer surface air temperatures above freezing so that snow is seasonal, except for the high latitudes of the Canadian Arctic Archipelago, northern Russia, and northern Greenland (Figure III-2.5). These northern high latitudes have desert climates and receive low levels of precipitation (less than 15cm annually of water equivalent). Precipitation totals increase southwards to 50 cm in southern Greenland and to 60-120 cm on Sakhalin Island.

Antarctica also has a desert climate. In summer Antarctica is surrounded by open water (Figure III-2.1) and has below freezing surface air temperatures (Figure II-2.11) so that snow occurs year round at the coast. Total precipitation is low, in the order of 20cm of equivalent water along the coast, though heavy snowfalls occur in summer when cyclonic storms pick up moisture from the surrounding seas and then deposit this moisture as snow along the coasts.

Annex E – Possible Vessel Spill Scenarios and Case Studies

There is a wide range of possible oil in ice vessel spill scenarios, which are illustrated herewith specific examples.

- Small (Tier 1) spills: for example from burst pipes or drums on the decks of a ship. This oil is normally contained onboard or results in minimal over-the-side discharge. Leakage of oil into ballast systems, which are subsequently discharged overboard, can result in potentially large fines if discovered through airborne or satellite surveillance.
- A major tanker accident along a shipping route could cause a large spill when, for example multiple compartments are pen-

etrated through a high-energy collision (e.g. iceberg or growler), grounding, or explosion and fire. Although less likely with double hull tankers, such an internationally significant Tier 3 incident could result in tens of thousands of tonnes of crude oil being spilt in the worst case.

- Spills occurring during the oil loading/unloading process at terminals due to a breaking hose or an open valve, offshore ship to ship transfers, and transfers at many Arctic communities where the lack of a dock or deep water port necessitates fuel transfers by floating hose to the beach. These spills are generally of moderate size (Tier 1), varying in volume from between a



Figure E.1 MT Mastera (106,000 DWT) operating in the Baltic. Delivered in 2003 as the first commercial ship to utilize the Double Acting Tanker (DAT) concept. The Mastera and her sister vessel Tempera represents the current generation of ice-going tanker design with double hulls, ice strengthening Baltic 1A Super, and the most advanced spill prevention systems (Photo: Aker Arctic).



Figure E.2 Docking a condensate tanker under challenging conditions of winter darkness and ice in Kirkenes Norway, 2006 (Source: Norlense).

few litres to a few cubic metres. Exceptions can result in much more serious incidents. For example, a rupture in the loading hose at the Statfjord platform on 12 December 2007 led to the second-largest spill in Norwegian petroleum history as 27,500 barrels (4,400 cubic metres) of crude oil were released into the sea. Although not in the Arctic or in ice, this accident illustrates that the risk for a much larger spill from loading is nevertheless possible.

- Loss of bunkers from structural break-up, collision, grounding or explosion: for example, with bulk carriers, container ships, fish processing vessels and cruise ships. A well-documented incident in Arctic waters (without ice) involved a Malaysian cargo ship the MV *Selendang Ayu* that grounded off Unalaska Island in Western Alaska's Aleutian Islands in December 2004. The vessel broke apart and spilled an estimated 10,412 bbl (1,242m³) of diesel and thick fuel oil. The spill resulted in an extensive and expensive spill response effort, impacted many kilometres of shoreline and resulted in the known deaths of 1,600 birds and six sea otters. No local OSRO was based at the Command Post port of Dutch Harbor,

over 1,000 km southwest of Anchorage, the nearest large marine staging area. More than 30 chartered vessels were involved to support the initial response and the subsequent shoreline cleanup programme. A special network of transponders was established in order to provide basic communications between vessels, field teams and the Command Post in this remote, mountainous region (Gallagher and Gudonis, 2008). Ice was not present in this case but the incident embodies the many challenges faced in responding to any vessel spill in a remote Arctic area, far from infrastructure and shore-based support.

The Norwegian *Godafoss* grounding incident was the most significant oil-in-ice incident response experienced in recent years and highlights the challenges faced in responding to spills under freezing conditions with mechanical recovery systems. Furthermore, the spill provides an opportunity to observe the advantages of a well-established regional cooperation agreement in action, the Copenhagen Agreement, which facilitated the integration of the Swedish Coastguard into the response operation. The incident occurred



in the Hvaler–Fredrikstad archipelago (Ytre Hvaler National Marine Park) in southern Norway, approximately 10 km from the Swedish border, in February 2011. At least two bunker tanks were breached and current estimates suggest approximately 939 bbl (112 cubic metres) of oil (IFO 380) was released

into the sea (ITOPF, 2011). The response efforts to deal with this spill are described further in Part V-3.

- Loss of bunkers through chronic leaking after sinking. The drift and spreading of the *Runner 4* oil spill in the ice-covered Gulf of

Figure E.3 *MV Selendang Ayu broken into two halves after grounding off Unalaska Island (Photo: US Coast Guard).*



Figure E.4 *Boom surrounding the Godafoss casualty in the ice-covered waters of the Ytre Hvaler National Marine Park, Norway (Photo: ITOPF).*



Figure E.5 Oiled ice from Runner 4 incident in Tallin Bay (Photo by Peeter Langovits/Postimees in Wang et al. 2008).

Figure E.6 Oil on the water surface among light ice cover on April 9, 2006 25 days after the sinking (Photo – Estonian Border Guard in Wang et al. 2008). (See Chapter V-2 for a discussion on detecting, monitoring and tracking spills in ice-covered waters).



Finland is an example of this type of scenario. The oil spill was caused by the sinking of the Dominican-registered cargo ship *Runner 4* on 5 March 2006, after collision with the Malta-registered cargo ship *Svjatoi Apostol Andrey*. This oil spill was very difficult to detect in the first week due to severe ice conditions. Response operations started when the wind pushed the ice floes away and the spill was observed in open sea areas. Two efforts were made to collect and control the oil spill, one during 15-19 March and the other on 9 April. A sea ice dynamics model was employed to simulate the evolution of the ice conditions. A comparison between the oil spill coverage and the sea ice movement suggests that part of the oil moved with the ice while the other part of it drifted together with the surface current (Wang et al., 2008).



Figure E.7 The capsized vessel *Monarch* floats next to the Granite Point oil platform in Cook Inlet. Drifting ice is visible in the background (Courtesy Anchorage Daily News 2/22/09).

- Penetration of fuel or internal slops tanks through collision between offshore supply vessels (OSV) and an offshore structure. An example of this type of incident occurred in Cook Inlet in January 2009 when a supply vessel, the *Monarch*, was pinned against the legs of the platform by rapidly moving ice while making a routine delivery. The vessel was overturned by the ice pressure and subsequently sank with an estimated 1,111 – 1,206 bbl (132 – 144m³) of diesel onboard. US Coast Guard efforts to pump-off the fuel were hindered by strong tidal currents. The seven-crew members were able to evacuate to the platform and were then transferred to shore by helicopter. Recovery of liquids from a vessel in this situation is dangerous and requires significant marine salvage resources.
- Loss of tow when demobilising or mobilising floating drilling units into and out of region. Although neither incident occurred in ice-covered waters, two recent events illustrate the type of accident that could occur in the presence of ice. In December 2012, the Kulluk conical drilling unit (Figures E.8A, B) lost its tow connection the Gulf of Alaska and grounded on Sitkalidak Island in the Gulf of Alaska. Fearing the loss of fuel oil and fluids onboard, a full oil spill response operation was mobilised. Fortunately, there was no sign of a hull breach or spill and the rig was salvaged (eventually assessed as damaged beyond repair and broken up).

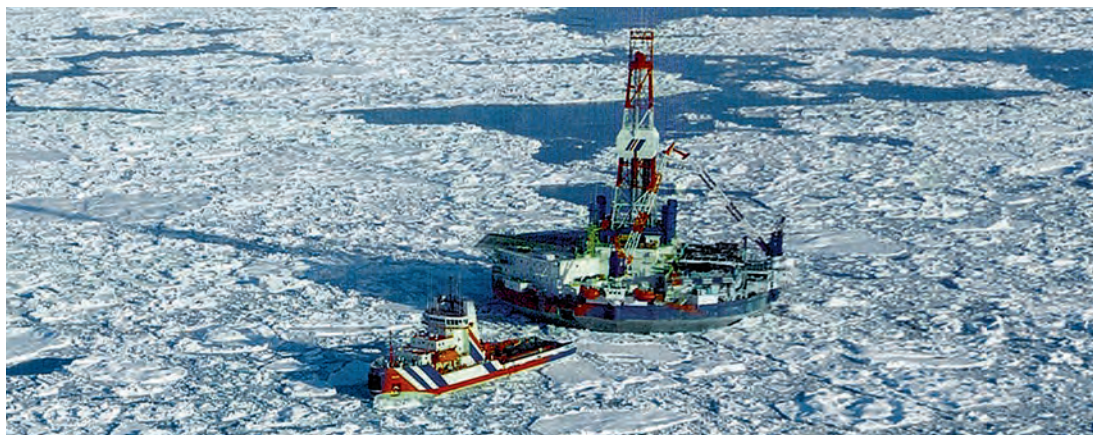


Figure E.8A The Kulluk conical drilling unit operating in heavy ice at the Pitsiulak site in the Canadian Beaufort Sea in 1984 (Photo: Gulf Canada). This rig was salvaged but written off after it grounded in Dec 2012 after losing its tow connection in the Gulf of Alaska in open water: Figure E.8B below.

In an incident one year prior to the *Kulluk* grounding, the *Kolskaya* floating drilling rig capsized and sank while under tow during a strong storm in the Sea of Okhotsk, killing 53 people and causing an insurable loss of over \$100 million. The drilling rig was not carrying any oil when it sank, but the incident led to concerns that similar severe Arctic weather could threaten other floating installations that store significant quantities of oil, such as FPSOs (Lloyds 2011).

The most recent example of a loss of tow

in Arctic waters involved a barge in the Canadian Beaufort Sea that went adrift in late October 2014 with ice forming (Figure E.9). Fortunately, the barge cargo tanks were empty and the maximum pollution risk from a total loss would involve only 30 bbl (3.6m³) of diesel fuel. The U.S. Coast Guard deployed a satellite tracking beacon on the barge once it entered US waters. A U.S. Coast Guard spokesperson said that it could be difficult to retrieve the barge because the ice was forming fast and officials had few vessel options

Figure E.8B Kulluk Arctic mobile drilling unit hard aground on Sitkaladik Island, Gulf of Alaska December 2012 (Photo: US Coast Guard).



Figure E.9 *Unmanned barge adrift after breaking loose from a tug while under tow during an October 2014 storm in the Canadian Beaufort Sea.*



(seasonal icebreakers had left the region already en route to home ports in the south). As of December 19, 2014 the barge was still intact and had drifted 500 miles (~300 km) to a position ~100 km west of Point Hope in

Russian waters of the Chukchi Sea. Sources: <http://www.cbc.ca/news/canada/north/ntcl-barge-adrift-in-beaufort-sea-along-alaskan-coast-1.2811585>, www.ktva.com/ghost-barge-in-russia-now-544/