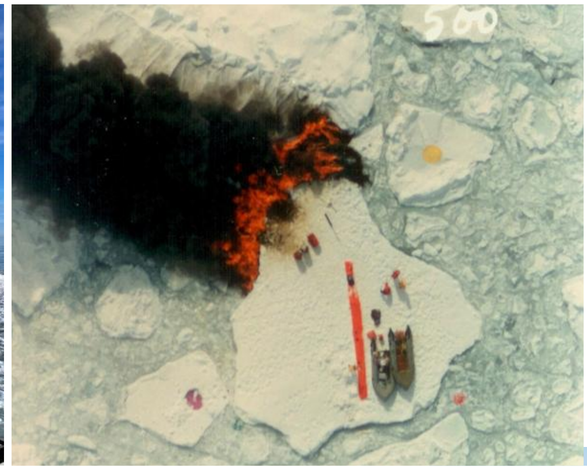
Great Lakes Oil in Ice Response Guide

Technical Report

September 2025

Great Lakes Oil in Ice Response Guide

Technical Report

U.S. DEPARTMENT OF COMMERCE • National Oceanic and Atmospheric Administration • National Ocean Service • Office of Response and Restoration • Emergency Response Division

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Funding for this guide was provided by the United States Coast Guard (USCG), Great Lakes Oil Spill Center of Expertise (GLCOE), in collaboration with the NOAA Office of Response and Restoration (OR&R) to develop a freshwater oil in ice guide for responders to assist in operations oversight, develop appropriate response objectives, and provide foundational knowledge for oil in ice tactics, safety, and logistical considerations. There is a separate **Operations Guide** that includes charts to assist in selection of appropriate response tactics based on spill conditions.

These reports were developed by Research Planning, Inc., Columbia, SC, in close collaboration with the GLCOE, Sault Ste. Marie, MI and NOAA Emergency Response Division, Seattle, WA. Jacqueline Michel was the RPI Project Manager. Co-authors of the reports were David Dickens (DF Dickins Associates, LLC), Chris Hall and Adam Kayser (Alaska Clean Seas), Mike Popa and Jim Elliott (T&T Marine Salvage) and CWO Joseph Torcivia (USCG) as technical editor.

Cover Page Photo Credits:
Upper Left – Ice pile ups on the Lake Huron shoreline 27 January 2024. Pancake ice forming in the foreground; Clarice Farina, Great Lakes Environmental Research Laboratory.
Upper Right – Burning crude oil spilled in slush between floes in very close pack ice during the 1986 Canadian East Coast "Oil in Pack Ice" experiment; R. Belore, S. L. Ross Environmental Research Ltd.
Lower Left – Clamshell bucket being used to scoop up oiled ice; Enbridge Pipeline.
Lower Right – Boom placed in slots cut through ice; Enbridge Pipeline.

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List of Abbreviations and Acronyms

ACS	Alaska Clean Seas
ARRT	Alaska Regional Response Team
AUV	Autonomous Underwater Vehicle
bbl	Barrel
cm	centimeter
CRREL	Cold Regions Research and Engineering Laboratory
EO/IR	electro-optical infrared
ft	feet
FMCW	Frequency Modulated Continuous Wave Radar
FOSC	Federal On-Scene Coordinator
FP	Fluorescence Polarization
g/cm^3	grams per cubic centimeter
GLERL	Great Lakes Environmental Research Laboratory
GLISA	Great Lakes Integrated Science and Assessment
GLOFS	Great Lakes Operational Forecast System
GNOME	General NOAA Operational Modeling Environment
GPR	Ground Penetrating Radar
ICECON	Ice Condition Index
IR	infrared
ISB	in situ burning
JIC	Great Lakes Joint Ice Center
kg	kilogram
lb	pound
MODIS	Moderate Resolution Imaging Spectrometer
NASA	National Aeronautics and Space Administration
NAIS	North American Ice Service
NOAA	National Oceanic and Atmospheric Administration
NWT	Northwest Territories
ODC	Oil Detecting Canine
ROV	Remotely Operated Vehicle
SAR	Synthetic Aperture Radar
SG	specific gravity
SM	Safety multipliers
UAS	Uncrewed Aerial System
USCG	United States Coast Guard
USNIC	U.S. National Ice Center
WMO	World Meteorological Organization

Key Terminology

Note: Refer to the *Key to Lake Ice Symbols* in Appendix A for corresponding numeric codes used in ice charts to define Stage of Development, Floe Size, and Concentration. Dimensions here are approximate, converted from metric to English units.

Stage of Development

New/Thin Ice: Newly formed ice less than 2 inches thick; A general term including frazil ice, grease ice, slush, and shuga.

- Frazil: Fine plates of ice crystals suspended in the water
- Grease Ice: Later stage of freezing than frazil when the crystals have coagulated to form a soupy matt layer on the water surface
- Slush: Snow that can appear as a viscous floating mass in water after a heavy snowfall into water at the freezing point
- Shuga: Accumulation of spongy white ice lumps a few inches across – formed by grease ice or slush

Thin Lake Ice: 2 to 6 inches thick

Medium Lake Ice: 6 to 12 inches thick

Thick Lake Ice: 12 to 28 inches thick

Very Thick Lake Ice: Greater than 28 inches – likely deformed ice

Floe Size

Pancake Ice: No defining size, typically 1 to 6 feet in diameter. See Figures 2-6 and 2-5.

Small Cake/Brash: The wreckage of other forms of ice accumulating in the water as fragments less than 7 feet across.

Ice Cake: 7 to 65 feet

Small Floe: 65 to 325 feet

Medium Floe: 325 to 1,650 feet

Big Floe: 1,650 to 6,550 feet

Vast Floe: 1 ¼ miles to 6 ¼ miles

Giant Floe: greater than 6 miles

Fast Ice: Continuous sheet extending out from shore – no defining size, often deformed by wave and wind action. See Figures 2-3 and 2-4.

Ice Concentration

Area of water surface covered by ice expressed in tenths, e.g., 1/10 = 10% coverage, 10/10 = 100% coverage of ice. See graphics on the next page.

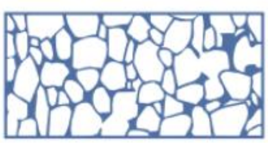
Ice Concentration

<1/10 Open water

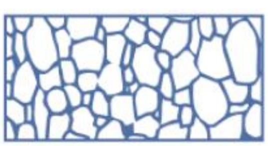
1-3/10 Very open drift

4-6/10 Open drift

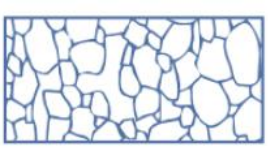
7-8/10 Close pack



9/10 Very close pack



9+/10 Very close pack



10/10 Compact/Consolidated Ice

1 Introduction

1.1 Purpose of this Guide

This guide to oil spill response in freshwater ice for U.S. Coast Guard (USCG) Federal On-Scene Coordinators (FOSCs) will assist with contractor oversight, developing appropriate response objectives, and provide foundational knowledge for oil in freshwater ice tactics, safety, and logistical considerations.

Several comprehensive publications cover the subject oil in ice response (e.g., API 2024; Hansen and Fitzpatrick 2017; Owens and Dickins 2015). This new guide builds on this material, as well as the results of many historical research studies on oil in ice response, and presents findings that apply most directly to freshwater winter environments in the Great Lakes.

1.2 Great Lakes Region

This guide addresses responses to spills in ice conditions on the Great Lakes, Associated Navigable Rivers, and the St. Lawrence Seaway from Lake Ontario to the Eisenhower Lock (Figure 1-1).

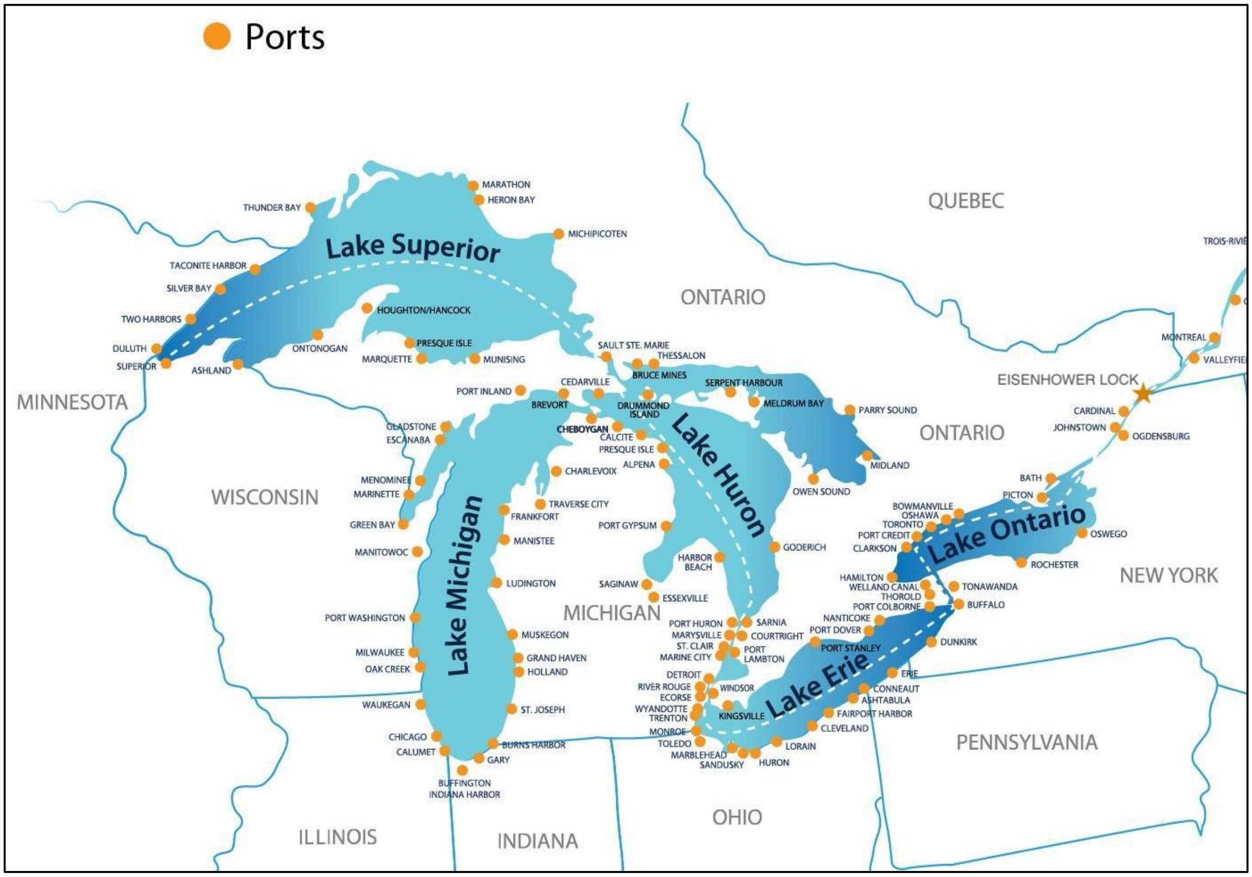


Figure 1-1. The Great Lakes Region covered by this guide, showing the major ports. The Eisenhower Lock is shown as an orange star.

1.3 Oil Types and Oil Transportation in the Region

The Hazardous Material Outreach Network (https://hazmaton.org/) summarizes the spill scenarios and risks associated with different modes of crude oil transport. Partners are the International Joint

Commission, Great Lakes Commission, and Sea Grant. Their web site as well as Davenport et al. (2024) contain maps of all the oil transport modes and on land facilities like refineries and marine terminals.

Of the active crude oil transportation modes in the Great Lakes, tanker trucks move the smallest total volume. They are most often used to transport crude oil short distances between terminals and refineries that cannot be accessed by pipeline. Trucks are far more likely to be used for transporting refined petroleum products than crude oil.

A very small amount of crude oil moves from terminals to refineries in the region by rail. However, most of the crude oil movement by rail in the region is “pass through” – moving toward downstream refineries on the east coast.

Based on Davenport et al. (2024), of the 20 million barrels (bbl) of petroleum products moved annually by vessels through the Great Lakes, 70% is comprised of asphalt, tar, pitch, and petroleum coke; 15% is distillate fuel oil; only 2.6% is residual fuel oil. There is currently no crude oil moved by tank ships (“tankers”) on the Great Lakes, though relatively small quantities of crude oil are transported to refineries by barge on rivers and canals within the basin. There is limited commercial vessel traffic in the Great Lakes in winter; icebreakers continue to support fuel transport to refineries by tug and barge throughout the ice season, and some commercial vessels continue to operate in ice before and after the locks close. Section 1.5 provides further details on the seasonality and timing of shipping vs. the onset and the end of the ice season.

Pipelines are the dominant mode of oil transport in the region (Figure 1-2). For example, Enbridge Line 5 moves 540,000 bbl of light crude oil, natural gas liquids, and light synthetic crude per day, year-round (equivalent to ~197 x 10^8 bbl/year).

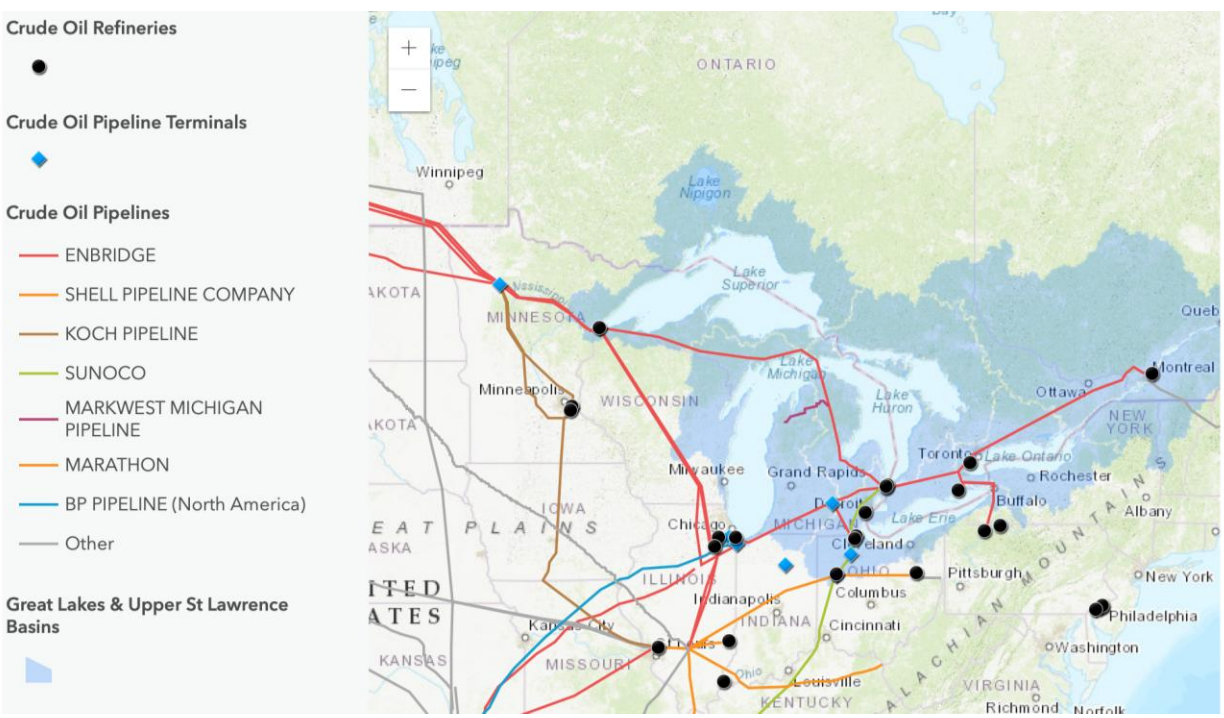


Figure 1-2. Crude oil refineries and pipelines in the Great Lakes Region (International Association for Great Lakes Research 2024).

1.4 History of Great Lake Oil Spills in Ice Conditions

Table 1-1 provides a summary of the history of Great Lakes oil spills in ice conditions, based on spill responses by Mike Popa (T&T) in the U.S. and Stephane Johnson (Triox) in Canada. Diesel fuel is the most frequently spilled product under ice conditions. Five of the eleven cases were from sunken vessels, mostly tugs.

Table 1-1. Great Lakes oil spills in ice conditions.

Date	Incident Name/ Location	Spill Type/ Volume	Scope	Response Actions
9 February 1994	Mistersky Power Plant, Detroit River	Diesel fuel/ 1,000 gal	Spill released from heating oil supply line into the Detroit River during very heavy ice flow conditions.	• Vacuum Recovery. • Recovery of contaminated ice using excavators and placing contaminated ice in 20-yard containers. • Containers of contaminated ice transported to heated building provided by the City of Detroit. • Melted ice discharged into approved wastewater treatment system. • Pockets of oil recovered using vacuum trucks.
2 February 1996	US Steel, Detroit River	Coal Tar/ Est. 900 gallons	Coal tar released from a steel plant coal tar tank supply line into the Detroit River. Work performed during high ice flow conditions on the Detroit River.	• Barge anchored in place to divert ice from recovery area. • Diver-assisted hydraulic pumping and environmental clamshell dredging. • Temporary tank farm installed for recovery of product and water from diver assisted pumping operation. • Portable filtration meeting MDNR regulatory permitting requirements for decanting filtered water back into Detroit River.
5 April 2004	M/V *Algonorth* Thunder Bay (Ontario) Canada	IFO (Interme-diate Fuel Oil)/ Est. 50 gallons	The bulk carrier discharged IFO the spill response performed in the spring, during ice melt conditions on Lake Superior	• Barge anchored in place to divert ice from recovery area. • Recover IFO with drum skimmer, vacuum truck and sorbents. • Pieces of ice covered with oil washed off in recovery area and treated ice placed in segregated area to melt. • Use of bubbling systems using compressed air and perforated weighted hose to: − Maintain open-water containment; − Melt ice containing oil; and − Aid in oil recovery. • Pressure wash and decontaminate vessel and drydock manmade structure. all wash- water recovered and disposed of at licensed wastewater facility.
13 December 2010	Tug *Ann Marie*, Saginaw River, Bay City, MI	Diesel fuel/ Est. 100 gallons	Tug sank at the dock during winter layup. Operations included spill response and tug salvage.	• Recover #2 diesel & engine oil with mini drum skimmer, vacuum truck & sorbents. • Contaminated Ice removed with clam shell placed in roll off boxes for disposal. • Vessel refloated, all hydrocarbons removed utilizing vacuum truck and disposed at licensed facility. • Pressure wash and decontaminate vessel. all wash-water recovered and disposed at licensed wastewater facility.

Date	Incident Name/ Location	Spill Type/ Volume	Scope	Response Actions
March 2010	Tug *Chris E. Luedtke* Lake Michigan Frankfort, MI	Diesel fuel/ 200 gal	Tug sank at the dock during winter layup. Operations included spill response and tug salvage.	• Recover spilled #2 diesel and motor oil with mini drum skimmer. vacuum truck and sorbents. • Wash oil with centrifugal pumps from surface of ice and recover. • Refloat tug. • Decontaminate the interior of vessel removing all contaminates and properly dispose.
March 2015	Train ~3 km NW of Gogama (Ontario) Canada	Synthetic crude Oil	A derailment of 37 train cars released approximately 695,000 gallons of crude oil into the water, and ground. Spill response began in early spring.	• Recover spilled synthetic crude oil with drum, and rope mop skimmer. vacuum truck and sorbents. • Extensive ice slotting used to facilitate boom deployments to contain product close to source. • Submerged gabion baskets filled with oil snare, observation at ice profiling holes and under-ice video used to detect presence of submerged or subsurface oil during response. • Extensive use of bubbling systems using compressed air and perforated weighted hose to: – Maintain open-water containment; – Melt ice containing oil; and – Aid in oil recovery. • Water injection used to flush oil trapped in the water layer between layers of ice. • Retaining ice along river banks during oil recovery prevented shoreline oiling. • Pieces of ice covered with oil washed off in recovery area and treated ice placed in segregated area to melt. • Pieces of ice with encapsulated oil removed and melted in frac tanks to recover oil. • Oil was collected from the river and placed in temporary storage tanks – oil and oily water were transported
4 February 2018	*Tug Robin Lynn*, Island Harbor Marina Canal, Lake St. Clair	Diesel Fuel, Bilge, Motor Oil/ Est. 150 gallons	Abandoned tug sank at dock. Operations included spill response and tug salvage. Tug prepared and towed to recycling facility in Port Colborne.	• Ice slotting and installation of a 12”x24” containment boom. • Spill recovery #2 diesel & motor oil recovered mini drum skimmer, vacuum trucks & sorbents. • Divers plug & patch prevent additional pollution. • Direct heaters utilized to heat frozen flooded engine room for refloating and pumping hydrocarbons from all tanks and bilge. • Complete survey and salvage/ refloating plan developed. • Prepare vessel for tow to recycle facility located in Port Colborne, Ontario Canada.
3 April 2018	Electric Cable, Straits of Mackinac	Dielectric fluid/ 600 gal	Anchor drag Straits of Mackinaw damaged electric cables on bottom lakebed running from Northern Michigan Lower to Upper Peninsula.	• Vessels positioned to divert ice flows from work area. Ice flows continuously based on wind. • Deploy side-scan sonar survey and locate damaged cables. • Develop Work & Safety Plan. • Deploy working class ROV recovery of dielectric cables. • Cap cables, which were returned to lakebed and anchored with cement mats.

Date	Incident Name/ Location	Spill Type/ Volume	Scope	Response Actions
11 January 2019	*F/V A.E. Clifford*, St. Louis River, Superior, WI	Diesel Fuel, Bilge, Motor Oil/ Est. 100 gallons	Abandoned fishing vessel sank at dock during winter layup. Operations included spill response and vessel salvage.	• Ice slotting and installation of a 12”x24” containment boom. • Recover spilled oil inside the vessel, remove contaminated ice, place in containers, heat and transport liquids for disposal. • Refloat vessel, removal all hydrocarbons from tanks and decontaminate vessel.
11 March 2019	Statler Street, Lake St. Clair	Heating Oil/ Est. 25-50 gallons	Private heating oil leaked into ground water and transported to Lake St. Clair.	• Ice slotting to install containment booms. • Recover heating oil with vacuum truck and sorbents. • Portable storage tanks and filtration system mobilized for treating recovered oily water for discharge back to Lake St. Clair. • Decanting permits required by State government.
21 March 2022	Tug *Lake Superior*, St. Louis River, Duluth, MN	Diesel Fuel/ Est. 75-100 gallons	Tug sank at the dock. Operations included spill response and vessel salvage.	• Containment boom deployed through broken ice to contain spilled #2 diesel and engine oil, survey vessel, develop pollution response plan, salvage/refloating plan. • Recovery of diesel fuel with a vacuum truck and sorbents materials. • Tug refloated, all hydrocarbons removed from vessel’s tanks, and bilge. • Vessel decontaminated, all waste disposed at licensed facility. • Chain pullers required for refloating.

1.5 Likely Spill Scenarios during Ice Conditions

As outlined in Section 1.3, a wide range of petroleum products is moved throughout the Great Lakes by vessels during the open-water shipping season and to a lesser extent during the winter months. Intra-lake vessel movements in and out of Lake Superior are controlled by the Soo Locks in Sault Ste. Marie, typically opening on or about March 25 and closing for maintenance on January 15 every year. Vessels left operating through ice during the period of lock closure tend to be limited to icebreakers and tugs supporting barges that move refined petroleum products short distances throughout the winter, ice conditions permitting. Figures 1-3 and 1-4 show an examples of articulated tug barges that can operate in high ice concentrations, carrying petroleum products and other cargoes.

Ocean-going vessels are limited to entering the Great Lakes when the St. Lawrence Seaway is open, typically from the last week in March to the last week in December (the January 5 closing in 2024 was the latest in Seaway history). After the Seaway closes, commercial inter-lake vessel traffic through ice is limited to transits through Lake St. Clair and the Detroit River (Lake Erie to Lake Huron), and the Straits of Mackinac (Lake Huron to Lake Michigan). Figures 1-5 and 1-6 show examples of continued vessel operations during the ice season.

Pipelines operate year-round, but only present a risk to the marine environment at a few specific locations where they cross over or under a waterway (e.g., Line 5 across the Straits of Mackinac) or run adjacent to a shoreline (Figure 1-2). In a geographic sense, although the potential spill size from a pipeline is large, the area of risk to the marine environment is localized to these specific locations.

Like pipelines, the risk of a spill from rail transport is limited to a low probability event involving derailment at bridge crossings or locations where the tracks run along the shore.

Figure 1-3. The tug *Michigan* with the barge *Great Lakes* normally moves petroleum products to the BP refinery at Whiting, IN. at the Port of Milwaukee WI. Photo: David Fasules.

Figure 1-4. Barge *Michigan Trader* and her tug *Dirk S. VanEnkevort* at the Port of Lorain on Lake Erie, 6 January 2023. Photo: Lance Aerial Media.

Figure 1-5. Freighter *Jason J. Calloway* operating through heavy ice in Lake Superior, 30 March 2014. Photo: NOAA/GLERL.

Figure 1-6. USCG Cutter in Lake Superior near Duluth, 26 March 2014. Photo: NOAA/GLERL.

Spill risks from tanker trucks would be limited to cases where a truck overturned or departed the highway or bridge adjacent to or crossing a water body.

For a spill from a land-based source (e.g., truck, train, storage facility, pipeline) to enter the marine environment with or without ice present, two important criteria need to be satisfied:

1. The spill needs to occur close enough to the shoreline that the oil naturally flows directly from a higher to lower elevation directly into the lake or river or through another less direct pathway such as a waterbody or storm drain; and
2. The product needs to be of low enough viscosity that it can flow over obstacles such as irregular terrain or other barriers in freezing temperatures.

A spill from a vessel can enter the lake directly, either at dockside (e.g., fuel transfer operation) or underway through an accident that breaches the cargo or bunker tanks. With the limited amount of marine traffic in the winter, the risk of vessel collisions is low. A more likely scenario would be bottom damage or fuel tank rupture through grounding, or damage at or below the water line through allision, for example by contacting docks or bridge piers. A release above the waterline during a transfer operation could lead to the oil being deposited on the ice surface alongside the hull. Damage below the waterline could lead to fuel oil or oil cargo being released into the water column beneath the ice. If the vessel sinks, chronic long-term leaks can persist over months or even years. In that case, buoyant oil could rise and be trapped under the ice.

A pipeline leak from corrosion or rupture (e.g., due to anchor dragging, ice damage, shore erosion) could lead to a rapid release over minutes to hours where the crude oil or natural gas liquid rises through the water column and becomes trapped under ice or exposed in openings and leads as mobile pack ice drifts over the release point.

Whether the released oil/product floats (rises) or sinks to the bottom depends on its specific gravity (SG) at the time of the spill and over time as it weathers and loses light ends or takes up sediment from the water. Typical SGs of petroleum products and oils moved through the Great Lakes Region by the primary transport modes of pipeline or vessel are:

<u>Pipelines</u>

- Light crude, light synthetic crude: 0.82-0.87, and natural gas liquids: 0.78

Vessels

- Asphalt /bitumen/petroleum pitch: 1.05
- Tar: 1.2
- Petroleum coke: 1.7-2
- Distillate fuel oil (diesel): 0.9
- Residual fuel oil: 0.98-1.03
- Diluted bitumen (Dilbit) – variable according to the % diluent type: 0.94 (variable)
- Marine diesel: 0.88 – 0.9
- Very low sulfur fuel oil: typically, 0.85 to 0.96

Note: Not all vessel oil cargoes will continue to be moved in the same proportion during the ice season. Percentages for the product types presented in Section 1.3 refer to annual tonnage without breaking down how much of each product is moved in open water vs. with ice cover. SG values increase for all products at colder temperatures. Values are quoted for 32°F where data are available.

In summary, spills from pipelines are likely to remain at or near the surface while many of the cargoes transported by vessel (e.g., asphalt, tar, and petroleum coke) could sink, presenting a very challenging recovery operation with ice present. Oils with SGs very close to 1.0 can quickly weather and take up sediment to become negatively buoyant and submerge to the lakebed. Oils that are neutrally buoyant can become trapped at depth in brash and slush ice, making access and recovery extremely difficult.

2 Primer on Freshwater Ice in the Great Lakes Region

2.1 Ice Information Sources

There is a wealth of real-time operational as well as archived graphical ice data available for the Great Lakes Region. Key sources are summarized here by agency and organization with links to some of the most important data sites for download and viewing graphical products.

North American Ice Service (NAIS)

The U.S. National Ice Center (USNIC) and the Canadian Ice Service work together to produce Great Lakes products during the ice season as the NAIS. These products include:

- Ice charts: Daily ice analysis of the Great Lakes, available in color or black and white, and separated into the eastern and western portions of the Great Lakes. These charts use the World Meteorological Organization (WMO) Egg Code nomenclature (displayed within an oval-shaped symbol, hence the "egg" nickname) to define ice concentration, stage of development (thickness), and floe size; see Lake Ice nomenclature and Codes in Appendix A;
- Outlooks: 30-day outlooks and an annual outlook that provide detailed ice condition information for the Great Lakes; and
- Seasonal summary: A recap and comparison of the Great Lakes ice season.

Notes:

- The Great Lakes Joint Ice Center (JIC) is a partnership between the U.S. Navy and NOAA.
- The USNIC is a tri-agency partnership between the U.S. Navy, NOAA, and USCG that operates the JIC.

USNIC also produces periodic ice charts for USCG Great Lakes (formerly District 9), divided into ice concentration, ice thickness/type, and a combination of both. Real time and archived historical charts are available for download files at: https://usicecenter.gov/Products/GreatLakesCharts

In addition, the Canadian Ice Service prepares periodic (unscheduled) ice charts of the St. Lawrence River based on visual observations from Canadian Coast Guard ships, aircraft, and helicopters. These products are only available for areas with known marine activity when ice is present.

Coverage within a given area may vary extensively, depending on flight patterns. There appear to be no operational ice charts showing real-time ice conditions in the upper St. Lawrence River (West of Eisenhower Lock).

NOAA Great Lakes Environmental Research Laboratory (GLERL)

Coastwatch (https://coastwatch.glerl.noaa.gov) is a nationwide NOAA program within which the GLERL functions as the Great Lakes regional node. GLERL has been exploring the relationships between ice cover, lake thermal structure, and regional climate for over 30 years. GLERL is not an operational organization in that their products are considered “near real time”. There may be gaps in coverage, and data could be delayed compared with the regularly scheduled operational ice charts produced by the NAIS.

To understand the timing of ice formation and the types of ice in the Great Lakes, GLERL and USCG use synthetic aperture radar (SAR) data to monitor six different types of ice, ice thickness, and ice cover. This risk assessment tool is known as the Ice Condition Index (ICECON). The USCG uses ICECON to identify areas that require ice-breaking operations and ship-transit assistance. The same tool could also provide valuable information on ice conditions affecting site assessment and response planning in the event of a winter spill. https://coastwatch.glerl.noaa.gov/satellite-data-products/ice-cover-classification/

GLERL also maintains a compilation of hundreds of photographs and videos of Great Lakes ice conditions collected from various sources. A number of these are used to show the visual appearance of different ice conditions in Section 2.2.
https://www.flickr.com/photos/noaa_glerl/albums/72157633501597864/with/8740493179

Great Lakes Integrated Science and Assessment (GLISA)

GLISA is a collaboration between the University of Michigan and Michigan State University supported by NOAA. Established in 2010, GLISA serves Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, Wisconsin in the U.S., and the Province of Ontario in Canada. It’s web site contains an overview of lake ice and the drivers governing the ice cover and seasonal variability of ice cover, focusing on long-term trends. Several graphic products illustrating the rate of change in ice seasons and duration of ice cover are included in Section 2.2. https://glisa.umich.edu/sustained-assessment/lake-ice/

NOAA maintains an extensive collection of still photos and videos showing images of different lake ice conditions at the shoreline and along shipping lanes. These views give an appreciation for the variability in the ice surface conditions coverage governing the level of difficulty in gaining access and possibly working safely on the ice. A small number of selected images are included in Section 2.2 as examples.
https://www.flickr.com/photos/noaa_glerl/albums/72157633501597864/

2.2 Ice Types and Terminology

The key differences between sea ice (formed from salt water) and freshwater ice include:

- **Salt content:** Freshwater ice has negligible salt content, whereas sea water ice contains a substantial amount of salt trapped within its crystalline structure.
- **Freezing point:** Fresh water freezes at 0°C (32°F), while sea water freezes at a lower temperature due to the salt, typically around -1.8°C (28.8°F).

- **Density:** The process by which freshwater 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 freshwater ice because salt water must 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 (28.8 °F) to freeze. The typical density of lake ice is approximately 0.917 grams per cubic centimeter (g/cm^3) at 0°C (32°F). This is slightly less dense than pure water, which is why ice floats. The density of sea ice is slightly less and typically ranges from 0.840 to 0.910 g/cm^3. The density of any ice can vary slightly based on factors like temperature, air bubbles, and impurities within the ice. Sea ice density is further influenced by the presence of brine; see further discussion below with the implications for spill response.
- **Formation and decay processes:** When sea water freezes, the ice crystals primarily form from the water molecules, rejecting most of the salt at the growing interface while creating brine pockets and vertically connected channels within the ice. As the ice warms in the spring these channels form a natural pathway for oil trapped within or beneath the ice to rise to the surface. This process usually occurs well ahead of break-up (by up to a month) while the sea water ice is still relatively thick and able to support on-ice activities. *In contrast, oil trapped under freshwater ice may remain trapped below the surface until just days prior to break-up, a point where the ice has lost most of its bearing capacity*. In terms of how oil interacts with the two types of ice, the timing of oil exposure on the surface is perhaps the most important distinction affecting response options.
- **Strength and structure:** Due to the brine pockets, sea water ice tends to be somewhat weaker compared to freshwater ice of the same thickness.
- **Expansion and contraction:** Compared to freshwater ice, sea ice exhibits a more complex pattern of expansion and contraction with temperature changes, primarily due to the presence of the brine pockets within the ice. These cause it to expand when cooling and even contract slightly when warming, the reverse of freshwater ice.

The USNIC uses the Canadian, “Manual of Standard Procedures for Observing and Reporting Ice Conditions” (MANICE 2005) to define the terminology for all forms of ice: sea ice, lake and river ice, and ice of land origin.

It is not possible in this guide to cover the full suite of ice nomenclature defined by the WMO. The Canadian Ice Service Lake Ice Fact Sheet (Appendix A) covers the Egg Codes used in the JIC ice charts, and defines the ice thickness, floe sizes, and concentrations (tenths of area coverage) and associated codes assigned to the various categories. *The Key Terminology section covers the important ice definitions and provides a graphic to visualize ice concentrations.*

The following sections cover some key distinctions in stage of development and floe size applicable to most lake conditions. Understanding these distinctions is important to considering how the different ice conditions may affect oil behavior and possible response options:

<u>Stages of Development of Lake Ice</u>: Important to determine safe ice bearing capacity and difficulty of vessel access to the spill site; see Section 2.5:

- New/Thin Ice: less than 6 inches thick
- Medium Ice: 6-12 inches thick
- Thick Ice: 12-28 inches thick

These ice stages are used in the ice tactics selection “stop-light” charts and checklists in the Operational Guide. Checklists are provided for the following ice conditions:

- New/Thin Ice
- Very Open Drift Ice
- Open Drift Ice
- Close Pack/Drift Ice
- Very Close Pack Ice
- Compact/Fast Ice

Floe Size: Important for determining the ability to put crews onto the ice – may be possible with big thick floes, and mechanical recovery – possible with large openings between floes but not with areas of expansive pancake ice or brash:

- Pancake ice: Variable sizes from 1 to 10 feet (ft) across with raised edges and ~4-5 inches thick
- Small ice cake or brash ice: less than 7 ft. *Note: Brash Ice refers to accumulations of floating ice made up of fragments that are the wreckage left from the break-up and fracturing of other ice forms.*
- Ice cake: 7 to 65 ft typically
- Small floe: 65 to 300 ft
- Medium floe: 300 ft to 1,600 ft
- Big floe: 1,600 ft to 1 nautical mile in extent; there may be some opportunity for crews to work on thick, big (or larger) floes with vessel support regardless of ice concentration
- Fast ice: Attached to shore. This is the main type of ice where teams can venture out on the ice surface with suitable precautions – typically limited to protected bays, close to shore, and in narrow waterways where the ice freezes shore to shore
- Strips of ice: No specific size but can interfere with booms and skimmers

Concentration (tenths of surface coverage): Important to determine vessel access and degree of natural oil containment. *Refer to the graphic in Key Terminology for a visual presentation of each concentration range.*

- <1/10 classed as open water: Favoring conventional mechanical recovery and in situ burning (ISB) with booms
- 1-3/10 or very open drift ice: Mechanical recovery with booms and skimmers still possible with effectiveness diminishing with concentration; insufficient natural containment to burn without booming
- 4-6/10 or open drift ice: Mechanical recovery effectiveness severely reduced; ISB difficult to execute without booms or sufficient natural containment by the ice to maintain oil thickness
- 7-8/10 or close drift ice: Very limited mechanical recovery without specialized vessels and over-the-side skimmers into isolated oil pools; ISB possible with good natural containment by the ice floes
- 9+/10 or very close pack ice: Isolated leads and fractures; some opportunity for crews to work on thick, big floes with vessel support
- 10/10 total ice cover and or fast stable ice: Most likely to support ice-based response operations with safety precautions and sufficient thickness of clear white ice

In addition to this limited review of ice terminology and the ramifications for response, there are many other ice features that can greatly influence how oil becomes incorporated into the ice and remains trapped, affecting the difficulty of access and recovery:

- Brash ice concentrated by wind action into thick barriers at the shore or along the edge of fast ice can retain neutrally buoyant oil at depth within the ice.
- Ice foot remaining attached to the shoreline after the fast ice has moved away – often comprised of deformed ice pileups and rubble making access to the oil difficult.
- Deformed ice comprised of ice pieces squeezed together by wind action and forced up and down to create rafted ice (ice sheets riding over each other), ridged ice (line or wall of broken ice) and hummocked ice (hillocks of broken ice that can cover large areas.
- Grounded ice in shoal water, often creating fields of ice hummocks and rubble.

GLERL uses a different ice nomenclature than the Joint Ice Center ice charts (Appendix A). Figure 2-1 shows an example ICECON radar satellite-based product for Lake Superior and upper Lake Michigan.

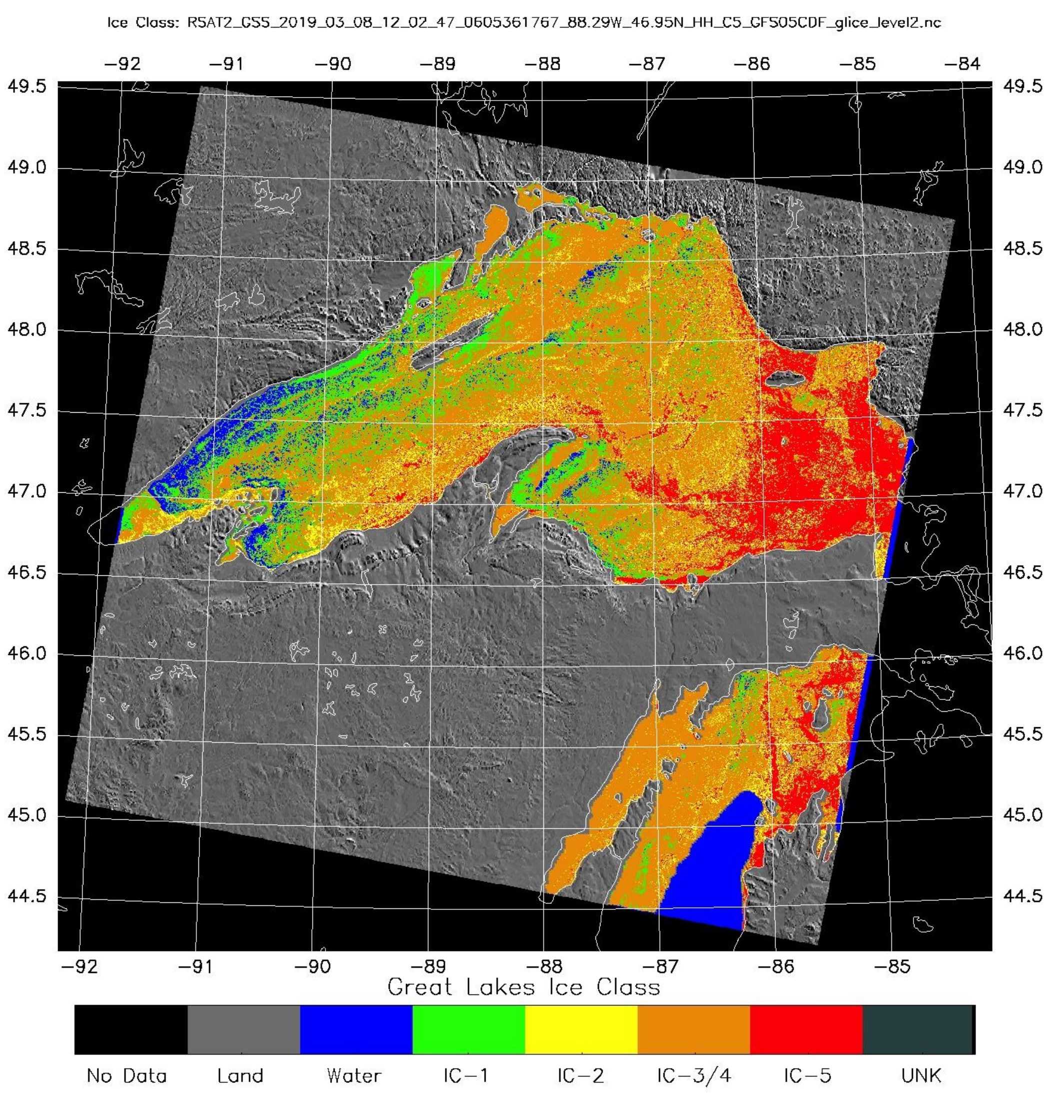


Figure 2-1. GLERL ICECON product showing ice conditions in Lake Superior and Northern Lake Michigan, 8 March 2008.

Table 2-1 shows the categories ICECON uses to describe ice conditions based largely on the ability to navigate.

Table 2-1. Satellite SAR ice type ICECON scale.

ICECON Categories	Description Example Ice Types	Thickness	Color	Impacts to Vessels
0	Calm Water (or below noise floor)	0″	Blue	No Ice present or imminent.
1	New Lake Ice	<2″	Green	Minimum ice concentrations and thickness, does not present hindrance to commercial navigation.
2	Pancake Ice	2″ – 6″	Yellow	Light Ice conditions present. Still open water areas. May be some hindrance to less ice-capable ships.
3	Consolidated Floes	6″ – 12″	Orange	Light-to-moderate ice conditions present. Less ice-capable ships may need icebreaker assistance for transit and /or be at risk for damage.
4	Lake Ice w/patchy crusted snow Snow/Snow Ice/Lake Ice	Up to 28″		Moderate-to-Heavy Ice conditions present. All Commercial ships may require ice breaker assistance for transit.
5	Brash	>28″ Up to 9-11m	Red	Heavy-to-extreme ice conditions. All transits require icebreaker escort. Approaching or exceeds capabilities of light icebreaker assets. Increased risk of damage to vessels.

Figures 2-2 to 2-6 show examples of the ice that forms naturally as opposed to the broken and churned up brash and ice cakes that characterize the shipping channels after multiple passes. Shore ice is often highly deformed with ice pushed by wind and waves into jumbled masses. Pancake ice forms are common throughout the ice season and can form along the shore or in deep water. The GLERL site shows many more photographs and videos of different ice conditions.
https://www.flickr.com/photos/noaa_glerl/albums/72157633501597864/with/8740493179

Figure 2-2. Thick ice cover in Lake Superior, 23 March 2014, viewed from the USCGC *Mackinaw*. Photo: GLERL.

Figure 2-3. Ice pile ups on the Lake Huron shoreline near Oscoda MI, 27 January 2024. Pancake ice forming in the foreground. Photo: Clarice Farina, GLERL

Figure 2-4. Deformed ice along the Lake Michigan shoreline near Grand Haven, January 2009. Photo: S. Darnell, GLERL.

Figure 2-5. Pancake ice in Lake Superior near Michipicoten, 23 March 2014. Photo: GLERL.

Figure 2-6. Close up of pancake ice in Whitefish Bay, Lake Superior, 22 March 2013. Photo: GLERL.

The presence of deep snow can not only submerge ice and create dangerous layers of weak snow ice, but hide oil from view. Episodes of severe lake-effect snow falls could hinder spill response.

In summary, ice charts and satellite-derived products provide valuable information on the regional ice environment for strategic planning purposes, answering questions such as:

- Expected range of ice thickness in the vicinity of the spill (stage of development) affecting the likelihood of staging equipment and personnel on the ice.
- Extent of ice coverage, providing a good indicator of the potential for rapid ice movements in response to winds and currents, while also determining the likelihood of implementing effective mechanical recovery and/or in situ burning.
- Floe sizes determining whether there is a possibility of operating from the ice surface (e.g., pancake ice 'no', big floes 'maybe').

When it comes to making "on the spot" decisions in the field about sending crews and equipment out onto the ice, a finer-grained level of detail is required to determine the risk level and to make an informed decision that ensures personnel safety (see Section 3). In this case, additional terminology associated with the integrity and strength of the ice may involve looking at the color of the ice from blocks or cores and assigning the thickness of the different ice layers in estimating the safe-bearing capacity. These factors are discussed further in Section 2.5 and lead into a review of ice and cold-weather safety practices in Section 3.

2.3 Summary of Great Lakes Ice Conditions

The following key points highlight general trends as they apply to the Great Lakes Region, focusing on duration, ice coverage (concentration), and thickness:

- **Variability**: Ice cover on the Great Lakes varies greatly from year to year, ranging from 95% to 12% maximum coverage (Figure 2-7). This variability is due to large-scale climate patterns that affect the jet stream, which in turn determines the air masses that move over the Great Lakes.
- **Ice formation**: Ice typically forms first near the shore and in protected bays and lasts longer over the deepest parts of the lake.
- **Ice thickness**: Ice thickness in the Great Lakes can range from 18–30 inches in coastal harbors and bays, to up to tens of feet in pressure ridges and shore pile ups.
- **Ice cover decline**: The Great Lakes have experienced less ice cover on average over the last 20–30 years. The decline has been most noticeable in the north, including Lake Superior, Northern Lake Michigan, and Huron, and in coastal areas. See discussion following.
- **Ice cover and lake-effect snow**: The amount of ice cover on the Great Lakes is closely linked to the amount and severity of lake-effect snow events. Years with low ice cover have a greater potential for large and impactful lake-effect snow events.

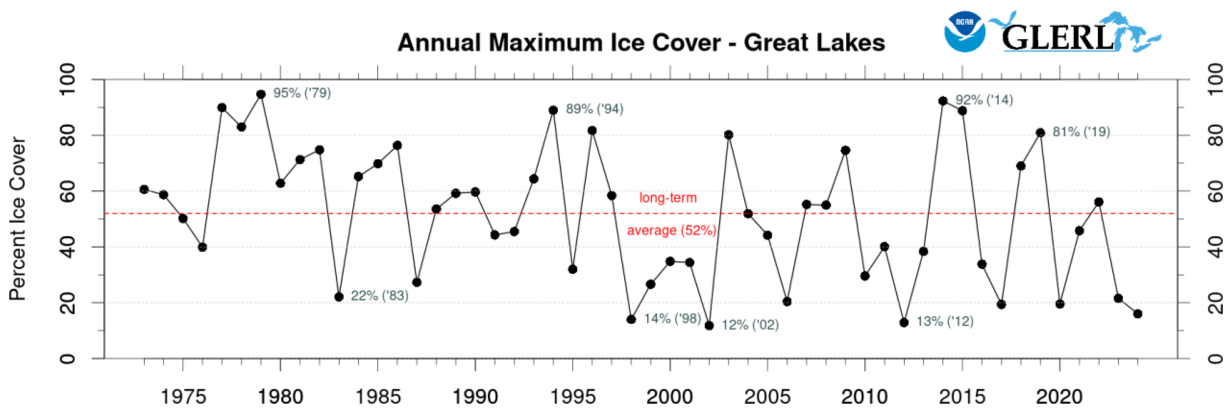


Figure 2-7. Annual variability in the maximum ice coverage in the Great Lakes from 1973 to 2024 (GLERL 2024).

The location of individual lakes makes them more or less susceptible to cold temperatures (north vs south), and lake depth plays a role in determining the lake's heat capacity or temperature "memory." Northern deep lakes, for example Lake Superior, are less sensitive to climate forcing because of their longer memory of water temperatures. Comparatively, Lake Erie is so shallow that ice can form quickly when temperatures are cold enough. Figure 2-8 contains snapshots of regional ice facts for each lake.

Ice conditions in connecting passages are controlled largely by winds and currents. The Straits of Mackinac commonly freeze entirely for a period in mid-winter. With the prevailing westerly winds, the Straits often become a congestion point, with ice often converging and ridging, leading to some of the thickest ice in the Great Lakes.

Another area more likely to provide thick stable ice cover is Whitefish Bay in southeastern Lake Superior, where shallow water and funneling of winds from the northwest cause the ice to become ridged and pushed into shore. In contrast, the Detroit River rarely completely freezes over due to the strong current and thermal discharge from power plants in Detroit and Windsor. Typical ice thickness is less than 4 inches and is not safe for on-ice operations.

Table 2-2 summarizes the typical period of peak ice cover displayed in these graphs. Lakes Superior, Huron, and Erie show the longest consistent ice seasons while Lakes Ontario and Michigan experience much shorter periods with substantial ice cover and very large swings in ice coverage within a given

Great Lakes

REGIONAL ICE FACTS

Factors influencing Great Lakes ice extent and thickness

Air temperatures: Ice forms and thickens when air temperatures drop below freezing and water temperatures cool. While winter air temperatures can fluctuate greatly due to winter storms, the northern lakes are more likely to experience consistently cold temperatures through the winter months. For this reason, northern areas are more likely to see thicker ice at the end of the season, and the last ice to melt is typically found in the northern bays of Lake Superior and in the North Channel of Lake Huron.

Water depth: Because shallow waters cool more quickly than deeper waters, ice forms first in coastal areas and this is usually where the thickest ice will be found. Lake Erie, being very shallow, is often completely ice covered in mid-winter. Other lakes with deeper basins will often remain ice free in their central parts.

Winds and storms: Winds and transient winter storms modify the distribution and form of the ice. Warm air from the south can melt thinner areas of ice. Large waves can break up areas of ice into smaller floes. Where winds push the ice away from the shore, it will disperse and open water leads may form. Where winds push the ice against a shore, it will become compact and may pile up into ridges.

Lake Superior

Median ice season: late-November to mid-May
Latest ice presence: early-June
Max ice cover: mid-March (37%)
Variability in max cover: 10% - 98%
Ice thickness: 45-85 cm (along coast)
Max thickness: ~25 m (pressure ridges)
Special ice features: In Whitefish Bay, shallow water and funneling of winds from the northwest cause ridging and compressed lake ice during the winter. Ice tends to be thicker than the rest of the mobile ice in Lake Superior.

Lake Erie and Lake St. Clair

Median ice season: mid-December to mid-April
Latest ice presence: early-May
Max ice cover: mid-February (85%) [Lake St Clair 100%]
Variability in max cover: 8% - 100%
Ice thickness: 25-45 cm (in coastal bays)
Max thickness: up to 20 m (pressure ridges)
Special ice features: Because of its shallow profile the water temperature can change fairly rapidly. This causes lake ice to form and melt much more rapidly in this lake than the other Great Lakes. Atmospheric temperature changes between above and below freezing can cause large fluctuations in ice cover on the Lake.

Lake Michigan and Green Bay

Median ice season: early-December to mid-April
Latest ice presence: early-May
Max ice cover: mid-February (20%) [Green Bay 100%]
Variability in max cover: 12% - 88%
Ice thickness: 45-75 cm (coastal harbours and bays)
Max thickness: 25-35 m (ridges in Straits of Mackinac)
Special ice features: Due to prevailing westerly winds, the Straits of Mackinac often becomes a congestion point for lake ice, with ice often converging and ridging, leading to some of the thickest ice on the Great Lakes.

Lake Ontario

Median ice season: end-December to early-April
Latest ice presence: late-April
Max ice cover: mid-February (14%)
Variability in max cover: ≤10% - 65%
Ice thickness: 20-60 cm (in bays)
Max thickness: significantly >60 cm (pressure ridges)
Special ice features: Lake Ontario has the lowest maximum ice coverage of all of the Great Lakes owing to its depth and its relatively warmer winters compared to the other lakes.

Lake Huron and Georgian Bay

Median ice season: early-December to late-April
Latest ice presence: mid-May
Max ice cover: mid-February (43%) [Georgian Bay late-February 85%]
Variability in max cover: 25% - 98%
Ice thickness: 45-75 cm (coastal harbours and bays)
Max thickness: up to 18 m (pressure ridges)
Special ice features: The lake ice in the St. Mary's river and North Channel becomes land fast during the winter. Breakup of the ice in these areas in the spring is influenced by icebreaking operations, speeding up the ice melt and breakup process.

*Median Ice Season is defined as the period during which median ice concentrations in the region are ≥1/10.

Environment and Climate Change Canada / Environnement et Changement climatique Canada

Canada

Figure 2-8. Ice conditions for each lake. Source: https://www.canada.ca/content/dam/eccc/documents/pdf/RegionalIceFacts_GreatLakes.pdf.

season. Except for Lake Ontario, all the lakes experienced their most severe ice seasons in 2014 and lightest ice season by far in 2024 (Lake Ontario's most severe season was in 1984). The Lakes commonly (50th percentile) see the first ice typically forming along the shore and in bays as early as late November (Superior) and as late as the end of December (Ontario). The last remaining ice disappears as late as early June (Superior) and as early as early April (Ontario).

Table 2-2. Summary of typical ice seasons for each lake. Period with sustained ice cover up to the maximum coverage noted in the table. Derived from graphs of annual ice cover vs. date produced by NOAA Coastwatch GLERL. https://coastwatch.glerl.noaa.gov/statistics/great-lakes-ice-concentration/.

Lake	Typical Ice Coverage Considered Significant for Each Lake	Ice Season with Significant Ice Cover (approx.)
Superior	80%	Feb 3 – Mar 31
Huron	65%	Feb 3 – Mar 20
Michigan	40%	Feb 10 – Mar 10
Erie	85%	Jan 10 – Mar 25
Ontario	30%	Feb 1 – Mar 10

As shown in Table 2-2, the season with significant ice cover vs. any ice, is much shorter – from as short as 28 days (40% cover or more) for Lake Michigan to 56 days (80% cover or more) for Lake Superior. Ice near shore and in protected areas such as Lake St. Clair typically lasts the longest, on the order of 60-90 days. Because the duration and extent of ice coverage is highly variable, average conditions are not a good indicator of what can be expected in any given year.

Lake ice typically forms first near the shore and in protected bay areas as shown in Figure 2-9. Figure 2-10 shows the days of close-to-complete ice cover (≥90%) on average per year (winter season) across the region. Lake Ontario and large expanses of Lakes Michigan and Huron rarely freeze entirely.

Figure 2-9. Ice cover on the shore of Lake Huron's Tawas Bay. Shallow bays like this one are the first parts of the Great Lakes to freeze. Photo: Gabrielle Farina, GLERL

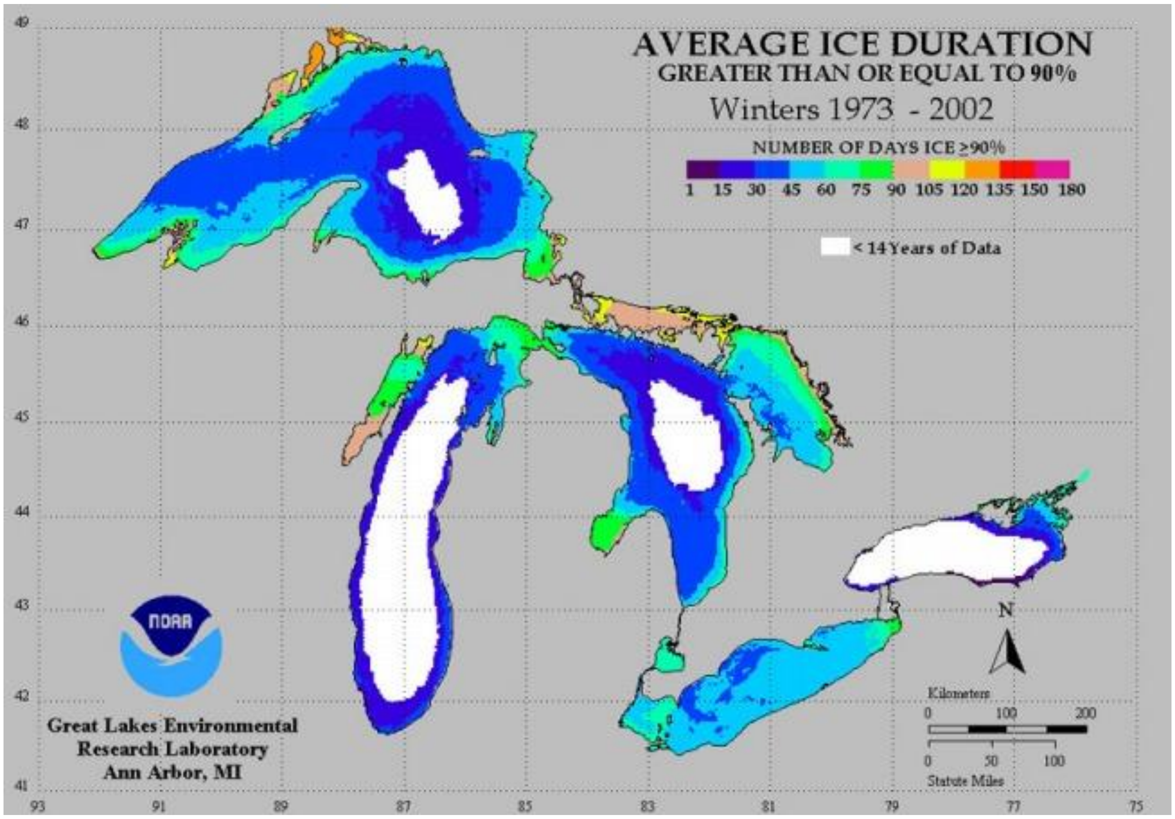


Figure 2-10. Great Lakes average ice duration (days/winter) map for days with at least 90% lake surface ice coverage. Source: https://glisa.umich.edu/sustained-assessment/lake-ice/.

Weekly variations in ice cover can be larger than the seasonal mean, indicating large "swings" in ice conditions can occur on short time spans. Lakes Michigan and Ontario experience the sharpest spikes and declines in ice coverage within a given season. The most effective means of appreciating the variability in Great Lakes ice cover is to view the interactive map on the GLERL website for 1973-2024. https://www.glerl.noaa.gov/data/ice/max_anim/anim.php.

MODIS satellite images provide a dramatic visual record of the ice cover variability between seasons and within a season. Figures 2-11 and 2-12 show selected visual scenes acquired by the MODIS satellites, Aqua and Terra, at 820 ft resolution. These images can provide a unique snapshot of simultaneous ice conditions in all five lakes, cloud cover permitting. Three images of Lake Erie show how different the ice conditions can be in the same time period from year to year (Figure 2-13).

The large fluctuations in ice coverage will greatly affect the viability of certain response tactics, especially those that rely on ice stability and thickness to support loads and safe on-ice operations (Sections 2.5 and 3.0). The frequent lack of a stable, safe ice cover for much of the winter season means that many of the on-ice mechanical recovery tactics presented in existing guides could be of limited use except for spills close to shore or in specific areas with recurring thick ice such as the Straits of Mackinac. Refer to a discussion of spill scenarios in Section 1.4.

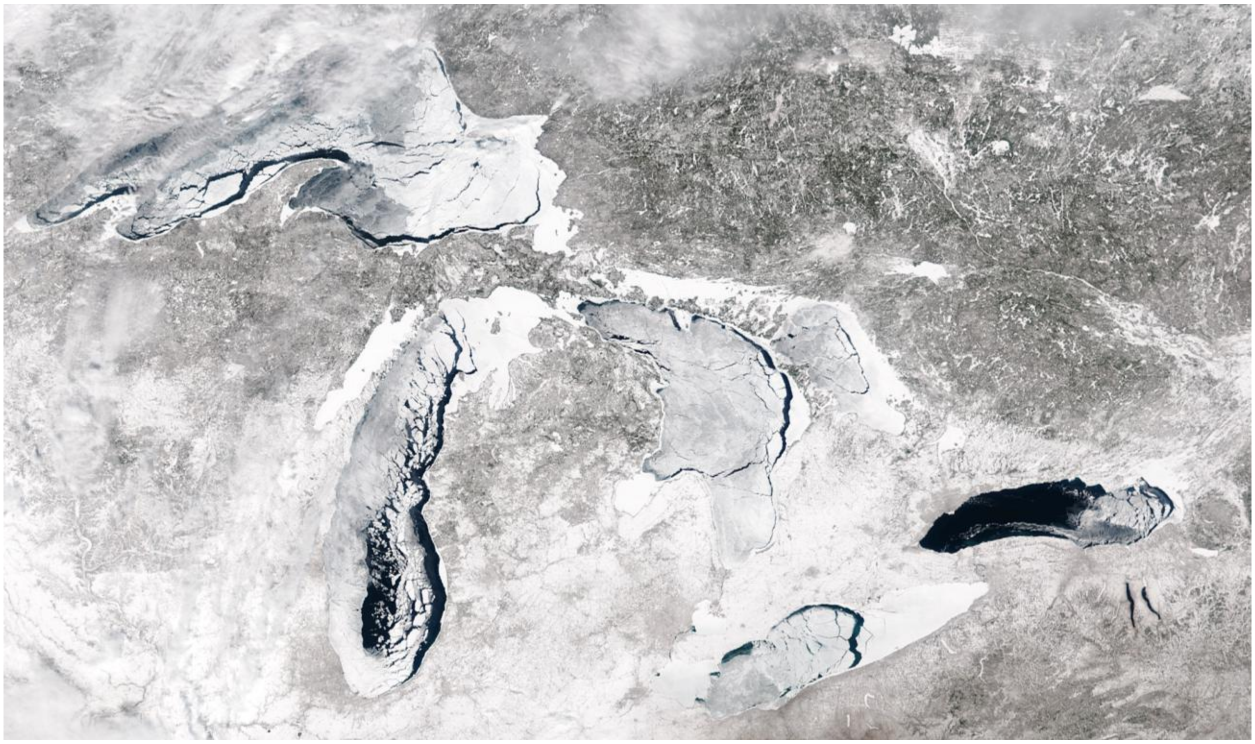


Figure 2-11. MODIS image 6 March 2014. Source: National Aeronautics and Space Administration (NASA). https://www.flickr.com/photos/noaa_glerl/albums/72157633501597864/

Figure 2-12. MODIS image 16 March 2014. Note the changes in ice distribution over a ten-day period since the earlier image in Figure 2-11, especially in the three northern Great Lakes. Source: NASA, https://www.flickr.com/photos/noaa_glerl/albums/72157633501597864/

Figure 2-13. MODIS images showing dramatic differences in the composition of Lake Erie mid-winter ice covers in different years: 8 March 2011; 6 March 2010; and 4 March 2009. Source: NASA. https://www.flickr.com/photos/noaa_glerl/albums/72157633501597864/

2.4 Regional Ice Cover Trends

The Great Lakes have experienced significantly less ice cover on average during the last 20-30 years compared to earlier years. The magnitude and timing of the recent shift to less ice cover varied spatially and temporally across the Region. Figure 2-14 shows that ice cover duration has decreased the most in the north (i.e., Lake Superior, Northern Lake Michigan, and Huron) and in coastal areas. There was no significant ice cover duration decline observed for Green Bay, sections along the Lake Michigan southern shoreline near Chicago, IL, much of the Lake Huron Michigan coastline, and a large part of Lake Erie.

The future of Great Lakes ice cover is not as straightforward as one would think, especially as global temperatures continue to rise. The future may hold another shift in ice cover but not necessarily in the downward direction. There is still the possibility of years with very high ice cover, such as the 2014 and 2019 ice seasons. Responders should prepare for increased variability – high ice cover years followed by low ice cover years, and vice versa. However, there are lake regions where ice cover has not declined (gray areas in Figure 2-14).

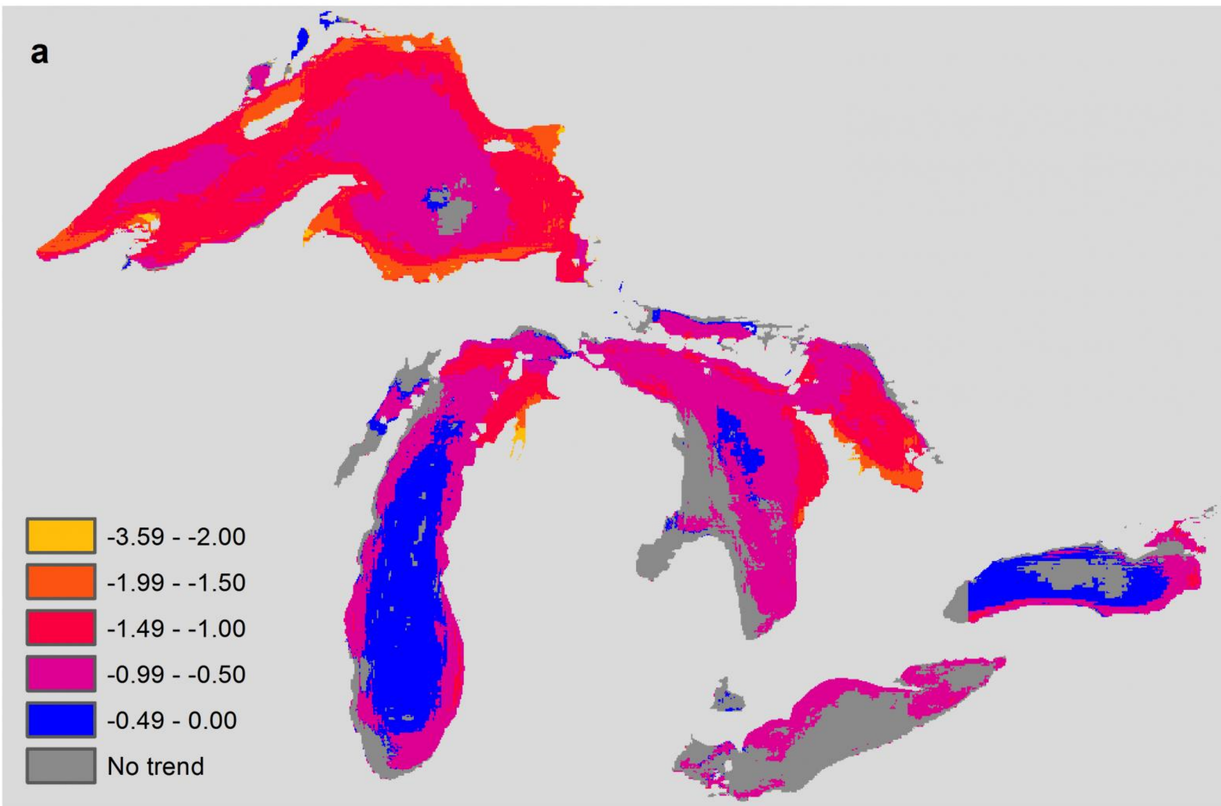


Figure 2-14. Rate of change (days/year) in seasonal ice cover duration (days/year) from 1973-2013, based on Mason et al. (2016).

2.5 Determining Ice Load Capacity

Considerations of safe ice loads are the key to implementing many of the on-ice tactics commonly used in areas with sustained, thick stable ice covers such as on the North Slope of Alaska. In the Great Lakes, the situation is very different. Whereas ice roads are common in the north, there are very few locations or winters in the Great Lakes Region when it is possible to build and maintain ice roads to take wheeled vehicle traffic for any significant length of time. This is mostly due to the lack of sustained low temperatures to freeze spray ice and build up the often-inadequate natural thickness. It may be possible to utilize snow machines and sleds, airboats, or small hovercraft to transport personnel and light equipment close to shore or in more confined bays and rivers, but not to safely venture into deeper water with moving floes.

With few exceptions, such as rivers or protected water bodies, the ice cover in the Great Lakes lacks both the level ice thickness and stability to support the use of heavy equipment such as loaders or dump trucks any significant distance from shore.

Where continuous stable ice exists around the spill site to potentially support response teams, it will be necessary to estimate the safe bearing capacity before putting equipment or personnel or lightweight equipment on the ice. This is done by profiling the ice for thickness and taking samples to determine the internal condition of the ice sheet (proportions of clear vs. white ice). Ice thickness data collected by drilling holes at set distances along a line or in a grid can be used to generate a profile of the ice thickness in the planned work area and along the planned access route from shore or a nearby vessel.

Profiling can be conducted remotely by flying a Ground Penetrating Radar (GPR) system at low level with a helicopter (Figure 2-15A), towing the GPR on a lightweight sled, or drilling a series of holes with an augur (2-inch flights with an electric power head are most efficient) along a line and or grid pattern to capture the natural variability due to snow cover and under ice currents (Figure 2-15B). The use of an airboat (Figure 2-15C) or small hovercraft is the safest means of checking ice thickness before setting foot directly on the ice. Alternatively, crews tethered by safety lines can pull an aluminum john boat with them for short distances when surveying a new area close to shore (Figure 2-15D).

Ice thickness can vary substantially over a small distance. Responders should not venture outside of an approved/cleared area without additional profiling. Chapter 3 discusses best practices and necessary personal protective equipment and procedures for venturing out on an undocumented sheet of ice. The following discussion focuses on how to determine the safe bearing capacity for different categories of support equipment.

The Michigan State Department of Natural Resources website contains excellent guidance on qualitatively assessing safe bearing capacity. https://www.michigan.gov/dnr/education/safety-info/ice. Their practical recommendations (aimed at ice fishers and snowmobilers but equally valid for responders) are:

- Strongest ice: clear with bluish tint.
- White opaque ice: ice formed by melted and refrozen snow – half strength.
- Grey ice Indicates presence of water and is unsafe.
- Stay off ice with slush on top.
- A sudden cold front with low temperatures can create cracks within a half-day.
- A warm spell may take several days to weaken ice and cause the ice to thaw during the day and refreeze at night.
- When temperatures vary widely, causing the ice to thaw during the day and refreeze at night, the result is a weak, "spongy" or honeycombed ice that is unsafe.
- If there is ice on the lake but water around the shoreline, be extra cautious.
- Stronger the current on the lake or river, the more likely the ice will give rise to dangerous thin patches or open water.
- Avoid areas of ice with protruding debris like logs or brush.
- Keep an eye out for dock bubblers or de-icers as the ice near these mechanisms will be unsafe.

- Ice covered by snow should always be considered suspect because:
  - Snow acts like an insulating blanket and slows freezing process
  - Ice under snow is thin and weak
  - A recent snowfall can melt existing ice

Figure 2-15. A) Profiling ice with a lightweight GPR mounted under a helicopter. Photo: D. Dickins. B) Auguring the ice to check thickness. Note the “buddy system”, flotation suits, and safety lines. Photo: Enbridge 2018. C) Air boat used for collecting samples on Lake Erie. Photo: Paul Glyshaw, GLERL. D) Ice core sampling, Green Bay, Lake Michigan. Photo: G. Leshkevich, GLERL.

Figure 2-16 is a schematic produced by the Michigan State Department of Natural Resources as a simple safety guide to anglers, snowmobilers, and residents. Users are cautioned that the range of thickness shown are for clear ice. The range reflects the variability in bearing strength due to natural causes such as temperature changes (warmer or colder). Refer to the more detailed discussion below with recommendations to arrive at a conservative effective thickness that can be used to estimate a safe bearing capacity.

Figure 2-16. Guide to minimum lake ice thickness required to support loads. Source: https://www.dnr.state.mn.us/safety/ice/thickness.html.

The following discussion provides a more rigorous approach to assess the ice-bearing capacity under different conditions. When a block of ice is pulled or a core taken, an accurate measurement of blue ice and white ice (counted as ½ the measured value) provides an initial measure of effective ice thickness. Safety multipliers (SMs) are then applied to modify this preliminary value and provide a more realistic measure of the safe effective ice thickness to use in load bearing calculations (below).

Total effective ice thickness = (Clear + 1⁄2 White) x Temp SM x Crack SM

Where:
Clear = clear ice thickness
White = white ice thickness
Temp SM = safety multiplier for temperature effects (Table 2-3)
Crack SM = safety multiplier for cracks in the ice (Table 2-4)

Example determination of effective thickness using the following scenario:

From an ice block cut out with a chainsaw, the total ice thickness is 16 inches comprised of 10 inches of clear ice and 6 inches of white ice. The air temperature has exceeded the freezing point periodically during the preceding 24 hours amounting to an estimated 6 hours above freezing. Non-intersecting wet cracks are visible.

Total effective ice thickness = 10 + (0.5 x 6) x 0.8 x 0.7 = 7.3 inches
Theoretically, this is just sufficient to support a moving car weighing up to 4,400 pounds on lake ice but not sufficient on river ice (Table 2-5). If the vehicle is to remain stationary the required lake ice thickness would increase to 11.8 inches. This compares closely to values published by the Minnesota Department of Natural Resources (Figure 2-16).

It must be emphasized that these bearing capacity estimates are just that – estimates. Any final decision to permit crews to venture out on the ice will depend on having solid evidence of ice thickness and clarity through profiling, careful attention to the presence of wide dry cracks or any wet cracks, and close attention to the temperature trends over the preceding 24 hours.

Table 2-3. Safety multiplier for temperature effects (Enbridge 2018).

Sudden Increase or Decrease in Air Temperature	Temperature Safety Multiplier
None	1.0
Drop of 9°F / 5°C or less	0.7
Drop of 9°F / 5°C to 18°F / 10°C	0.5
Drop of 18°F / 10°C or more	0.4
OR	
If the air temperature has exceeded 32°F / 0°C in 6 of the preceding 24 hours	0.8
If the air temperature has stayed above 32°F / 0°C for 24 hours or more	Unsafe conditions, discontinue on-ice work

Note: The ice cover should be checked for cracks when the air temperature drops by more than 36°F (20°C) over a 24 hour period according to the Department of Transportation Northwest Territories (NWT) (2015). Any time there are sudden and extreme temperature changes, the ice cover should be checked for cracks or other features that can compromise the load capacity. The NWT guide to Safe Ice Construction is comprehensive and clearly presented with excellent graphics (https://www.inf.gov.nt.ca/sites/inf/files/resources/0016-001_norex_ice_road_constr._web.pdf).

Table 2-4. Safety multiplier for cracks in the ice (combining recommendations from Enbridge 2018; NWT 2015).

Type of Crack	Crack Safety Multiplier
None	1.0
Dry cracks less than 2 cm (3/4 inch) wide	1.0
Refrozen cracks	1.0
Non-intersecting dry cracks wider than 2 cm (3/4 inch)	0.8
Intersecting dry cracks wider than 2 cm (3/4 inch)	0.6
Non-intersecting wet cracks	0 – suspend operations[1]
intersecting wet cracks	0 – suspend operations[1]

[1] Enbridge calls for continued operations with wet cracks with safety multipliers of 0.7 and 0.5 respectively for non-intersecting and intersecting cracks. The NWT Government Guide to Safe Ice Construction calls for cessation of all operations on the ice with any wet cracks. This is understandable given that the NWT guidelines are oriented to heavier construction equipment and vehicles involved in building ice roads and ice bridges. However, the need for absolute safety of response personnel in this response guide supports the adoption of the NWT recommendations in this case, pending a case by case on-site evaluation (https://www.epa.gov/sites/default/files/2018-11/documents/enbridge_inland_spill_response_tactics_guide_1.pdf)

The weight-bearing capacity of the ice can be established for four different risk levels: Low, Tolerable, Substantial and Extreme for both River and Lake ice, by using Gold's 1971 formula (below).

Gold's formula is:

$P = A\,h^2$

Where:

P = kilograms (kg) weight allowed.

A = kg/cm². Values typically assigned to represent different risk levels are: **Low** A= 3.5 or 4 (river or lake); **Tolerable** (with enhanced monitoring) A=5; and **Acute** (extreme risk) A=6.

h = effective ice thickness in centimeters. See the example above showing how to arrive at an effective thickness by applying safety multipliers to adjust for cracks and temperature.

It is important to remember that Gold's formula is a simplification and has limitations, especially when dealing with complex scenarios involving different types of ice, varying load distributions, or dynamic loads. It is a useful starting point for understanding ice bearing capacity but should always be used with caution and combined with other safety measures.

It is recommended that oil spill responders stay in the low-risk category for all operations. For Gold's formula, that means using an "A" rating of 3.5 on rivers or 4 on lakes. It may be possible to move up to the next highest risk category when water depths are shallow and additional safety measures are put in place, such as flotation on heavier equipment.

Note that lake ice generally supports a somewhat higher load than river ice at the same risk level (~15%) because the still water in a lake allows for a more uniform and thicker ice sheet to form, while the flowing current in a river constantly undermines and weakens the ice, resulting in a less stable and thinner ice cover.

Gold's formula Is safe to use for moderate loads at the lowest risk value of 4 up to the category of heavy truck (typically 15,000 to 17,500 pounds). A D3 CAT at ~21,000 pounds is at the juncture of where continued use of this widely used formula entails significantly higher risk. For heavier loads representative of larger construction equipment like bigger Cats, loaders and scrapers, a different engineering approach should be used based on a limiting ice stress design approach (see discussion following) applied by a registered civil engineer. See the explanatory Note 2 attached to Table 2-6.

The formula provides a weight-bearing capacity for an ice sheet over a radius of 100 ft applicable to moving loads (i.e., in continuous motion). For stationary loads and long-term working at one site, the safe ice thickness needs to be increased substantially.

Tables 2-5 and 2-6 show the load bearing capacity for moving and stationary loads used by Enbridge in the section on Cold Weather and Ice Tactics in their Inland Spill Response Tactics Guide (Enbridge 2018). Values are only shown for the range of loads where Gold's formula is considered valid, i.e., up to ~17,650 pounds (lb) (see table notes). River ice is generally weaker than lake ice, mainly due to the higher likelihood of encountering white ice coupled with the unpredictable effects of strong currents leading to patches of thinner ice. Typically, researchers have applied a 15% reserve to compensate for these effects.

Table 2-5. Safe ice load bearing capacity for continuous travel (Enbridge 2018).

Total Effective Ice Thickness (inch/cm)		Permissible Load
Lake	River	
2.0 / 5.1	2.4 / 6.1	One person on foot
3.1 / 7.9	3.5 / 8.9	Group in single file
7.1 / 18.0	8.3 / 2 1.1	Passenger car 4,400 lb / 2,000 kg
7.9 / 20.1	9.1 / 23.1	Light truck 5,500 lb / 2,500 kg
10.2 / 25.9	11.8 / 29.9	Medium truck 7,700 lb / 3,500 kg
13.8 / 25.1	16.1 / 40.9	Heavy truck 15,500 – 17,500 lb / 6,800 – 8,000 kg

Table 2-6. Safe ice load bearing capacity for stationary loads and working on the ice (Enbridge 2018).

Total Effective Ice Thickness (inch/cm)		Permissible Load
Lake	River	
7.9/20.1	9.1/23.1	2,200 lb / 1,000 kg
11.8/29.9	13.8/35.1	4,400 lb / 2,000 kg
17.7/44.9	20.5/52.1	8,800 lb / 4,000 kg
28.6/29.9	27.2/69.1	17,650 lb / 8,000 kg

Table Notes:

1. When multiple stationary loads are on the ice in the same working area, separate them 200 times the minimum total effective ice thickness required for the larger of the two loads.
2. Gold's 1971 formula is still commonly used by institutions, Provincial and State governments in the U.S. and Canada to recommend the safe bearing capacity of ice sheets (e.g., the API Winter Oil Spill Recovery Tactical Guidance Document, 2024). However, many contemporary models of heavy equipment have load configurations do not resemble the general load configuration utilized by Gold in the development of his original formula. Recent engineering analysis demonstrates that the use of this formula for heavy construction equipment (e.g., D3 Cat and heavier or >20,000 pounds) could risk a life-threatening ice break through (Fitzgerald and van Rensburg 2024). They calculate that using large excavators (53 metric tonnes) and heavy dozers (40 metric tonnes) as examples, the use of Gold's formula to determine the required ice thickness will result in predicted flexural tensile stresses in the ice that exceed the recommended maximum design stress by 56%–71%. For cases where the ice in the Great Lakes is thick enough and stable enough (typically 15 inches or more) to consider moving or parking heavy equipment on the ice, Gold's formula should not be used to estimate safe loads. Instead, organizations seeking to safely operate heavy equipment on floating ice covers should obtain professional engineering advice utilizing an allowable stress design approach.

3 Ice Safety Best Practices and PPE for Responders

Oil spill response operations on ice are inherently dangerous and complex. They pose significant risks to personnel and are challenging to execute and sustain. Risks may vary with each operation, but adhering to basic guidelines and aligning with the safety policies of involved companies and agencies helps strengthen risk analysis and mitigation planning. To ensure a safe and effective response, coordinate and communicate early and often with appropriate Subject Matter Experts (SMEs). For USCG members, all actions must also follow USCG, District, and Unit policies and guidance (see USCG SME and reference list as a starting point).

USCG internal SMEs for coordination (non-inclusive):

- District Response Advisory Team (DRAT) Strike Force
- HSWL Safety Environmental Health Officer (SEHO)
- Ice Rescue Unit

USCG internal guidance (non-inclusive):

- Boat Operations And Training (BOAT), Volume I COMDTINST 16114.32 (series)
- Cleveland SAR Plan D9 INST M16100.11
- Diving Program Manual COMDTINST M3150 (series)
- Ice Rescue Operations (IROPS) Tactics, Techniques, and Procedures (TTP) – CGTTP 3-50.1E
- Marine Environmental Response and Preparedness – COMDTINST 16000.14 (series)
- Rescue and Survival Systems Manual - COMDTINST M10470 (series)

When unsafe conditions arise, workers must be empowered to stop the job until the conditions are made safe. Clear stop-work criteria must be developed and communicated to workers, along with expectations for their proper use. Additionally, reporting procedures for unsafe conditions, injuries, or other critical information should be established and clearly conveyed to all personnel.

An in-depth risk analysis should be conducted to identify hazards, evaluate risks, and implement controls to effectively eliminate or mitigate those risks. Table 3-1 identifies common hazards and controls for work on ice. Figure 3-1 shows an example of a hazards analysis and flow chart.

Table 3-1. Common hazards and controls for work on ice.

Hazards	Controls
Hypothermia	Warm Clothing, Warm Up Cycle
Falls	Traction Devices, Contact Points
Personnel or equipment breakthrough	Profile and Weigh, Ice Plan, Harness, PFD
Frostbite	Observation, Warm Clothing, Warmup
Unstable work surfaces	Work from Stable Platform (e.g., airboat)
Soft tissue injuries	Personal Protective Equipment, Stretching
Engulfment	PFD, Medical/Rescue Teams, Safety Line & Harness
Chemical substance hazards	Chemical Clothing, Respirator

Of the risks associated with ice operations, the most significant is the potential failure of ice to support personnel and equipment. Section 2 outlines ice conditions in the Great Lakes, including tactics for profiling and assessing ice thickness, quality, and load-bearing capacity. Given the dynamic nature of ice in the Great Lakes, proper assessment is essential to ensure safe operations.

Before initiating response operations or supporting functions, a thorough assessment of ice conditions in the area must be conducted (see Section 2.5). A profile team should use an ice auger or profiling drill to evaluate the ice (Figure 2-15D). It is recommended that profiling teams wear PFDs (personal flotation devices) and body harnesses with safety lines. Line tenders should operate from a safe location such as the shoreline, grounded ice, previously profiled solid ice, or equipment surfaces such as amphibious vehicles, airboats, or johnboats.

While profiling, the team should probe for possible thaw pockets and voids under the snow, especially around buried infrastructure, pipelines, in rubble areas, and in the transition from shoreline to ice.

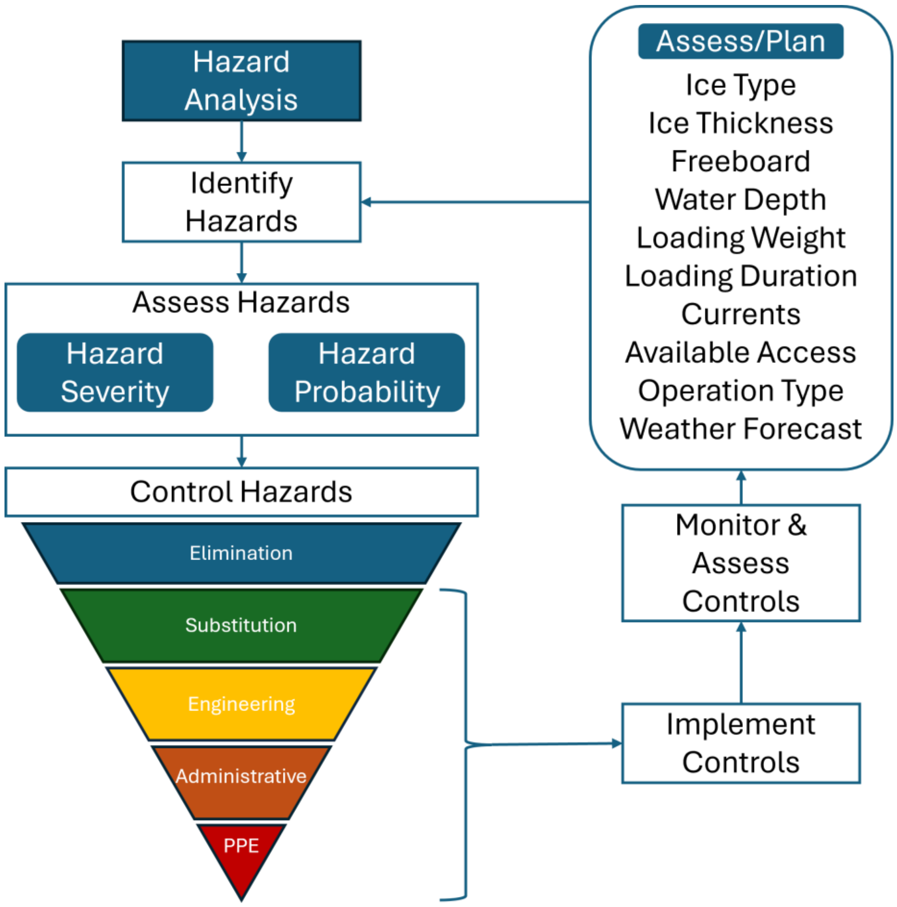


Figure 3-1. Hazard analysis and control flowchart.

At the conclusion of ice profiling and assessment, the team should clearly define safe areas and transit routes for personnel and equipment. Additionally, they should evaluate the need to designate on-ice staging areas, such as recovered material stockpiles and long-term equipment parking. Throughout operations on ice, it is important to regularly inspect routes and work areas—daily or once per shift, especially as conditions change.

Developing and distributing a detailed Ice Safety Plan is best practice. Components may include:

- Identified hazards and controls
- Ice profiling process
- Weight, duration, and speed limitations
- Visuals: Profile grid map, travel routes
- Weather forecast
- Ice movement survey
- Required PPE
- Required equipment and capabilities (e.g., amphibious vehicles, roof-escape hatches)
- Communications Plan
- Medical and Rescue Plan
- Post-immersion care

Workers should be notified whenever the plan is updated.

Basic PPE: Ensuring that personnel are adequately protected when working on the ice and in the cold must be a top priority. Personal preference may enter into the choice of equipment, but the safety aspects must be properly addressed. For example, when wearing a face covering with safety glasses or goggles, eye protection may quickly fog up, resulting in people taking them off and being exposed to eye injuries. Individuals must try different styles and find what works best for them to enable all of the PPE to be worn properly. PPE may include the options in Figure 3-2.

Government and industry personnel are reminded to follow their organization-specific PPE policies and guidance for cold-weather and oil spill response operations.

Options

- Base layers
- Layered clothing to allow for insulating air between the layers
- Breathable, warm outer clothing
- Waterproof outerwear in wet conditions
- Flotation suits (as required for conditions and duties)
- Warm hat and face covering as necessary
- Safety glasses or goggles
- Hard hat
- PFD and safety harness (must be outermost layers)
- Warm, safety toe footwear
- Traction devices – must be worn over chemical resistant booties
- Warm work gloves and chemical resistant outer gloves
- Appropriate chemical-resistant clothing as outermost layer under flotation devices and safety harnesses

Figure 3-2. Proper PPE for cold-weather operations. PPE options are shown to address the different hazards potentials of oil spill response on ice. Credit: ACS.

Work/Warm-up Cycles: As ambient air temperatures drop and/or wind speeds increase, the risk of cold-weather injuries to workers rises significantly. To mitigate this, a schedule for work and warm-up cycles should be established based on ambient air temperature, wind chill, and company or agency policy. The American Conference of Governmental Industrial Hygienists (ACGIH) offers recommended guidelines for these cycles (Figure 3-3).

Warm-up Facilities: Heated and covered facilities should be made available to allow both personnel and equipment to warm up as needed. These facilities should provide protection from the elements and be situated in a safe, easily accessible location. Additional details can be found in Section 4.3.

Dehydration: Dehydration is a common issue in cold environments and can increase the risk of cold-related injuries due to significant changes in blood flow to the extremities. To combat this, warm, calorie rich drinks and soups should be provided at the work site to supply both calories and fluid volume.

Weather Conditions: During on-ice operations, changing weather conditions can introduce additional safety hazards. Winter storms, blowing snow, large temperature swings, and high winds can reduce visibility, increase the risk of frostbite, and cause significant ice movement. Regularly monitor weather forecasts to proactively prepare for these conditions and mitigate their impact on operations.

Ice Degradation: Response operations can degrade the ice in the work area. Many of the tactics utilized in recovering oil in ice involve the removal of ice (Figure 3-4).

<table>
<tr><th colspan="11">ACGIH Work/Warm Schedule for Light Work Over a 4-Hour Shift</th></tr>
<tr><th></th><th colspan="2">No Wind</th><th colspan="2">5 mph Wind</th><th colspan="2">10 mph Wind</th><th colspan="2">15 mph Wind</th><th colspan="2">20 mph Wind</th></tr>
<tr><th>Air Temperature in °F Sunny Sky</th><th>Max Work Period</th><th>No. of 10 min Breaks</th><th>Max Work Period</th><th>No. of 10 min Breaks</th><th>Max Work Period</th><th>No. of 10 min Breaks</th><th>Max Work Period</th><th>No. of 10 min Breaks</th><th>Max Work Period</th><th>No. of 10 min Breaks</th></tr>
<tr><td>10 to 14</td><td colspan="2" rowspan="4">No recommendation</td><td colspan="2" rowspan="3">No recommendation</td><td colspan="2" rowspan="2">No recommendation</td><td colspan="2">No recommendation</td><td>120 min</td><td>1</td></tr>
<tr><td>5 to 9</td><td>120 min</td><td>1</td><td>120 min</td><td>1</td></tr>
<tr><td>0 to 4</td><td>120 min</td><td>1</td><td>120 min</td><td>1</td><td>75 min</td><td>1</td></tr>
<tr><td>-1 to -5</td><td>120 min</td><td>1</td><td>120 min</td><td>1</td><td>75 min</td><td>2</td><td>55 min</td><td>2</td></tr>
<tr><td>-10 to -14</td><td>120 min</td><td>1</td><td>120 min</td><td>1</td><td>75 min</td><td>2</td><td>55 min</td><td>3</td><td>40 min</td><td>3</td></tr>
<tr><td>-15 to -19</td><td>120 min</td><td>1</td><td>75 min</td><td>2</td><td>55 min</td><td>3</td><td>40 min</td><td>4</td><td>30 min</td><td>4</td></tr>
<tr><td>-20 to -24</td><td>75 min</td><td>2</td><td>55 min</td><td>3</td><td>40 min</td><td>4</td><td>30 min</td><td>5</td><td colspan="2" rowspan="6">Non-emergency work should stop</td></tr>
<tr><td>-25 to -29</td><td>55 min</td><td>3</td><td>40 min</td><td>4</td><td>30 min</td><td>5</td><td colspan="2" rowspan="5">Non-emergency work should stop</td></tr>
<tr><td>-30 to -34</td><td>40 min</td><td>4</td><td>30 min</td><td>5</td><td colspan="2" rowspan="4">Non-emergency work should stop</td></tr>
<tr><td>-35 to -39</td><td>30 min</td><td>5</td><td colspan="2" rowspan="3">Non-emergency work should stop</td></tr>
<tr><td>-40 to -44</td><td colspan="2" rowspan="2">Non-emergency work should stop.</td></tr>
<tr><td>-45 to below</td></tr>
</table>

Figure 3-3. ACGIH Recommended Guidelines for work/warm up schedules in cold-weather conditions.

Figure 3-4. Ice degradation can come from many sources in the response including warm hoses, burning operations, flushing, and cutting ice for containment and recovery. Photos: ACS.

Atmospheric Monitoring: Atmospheric hazards are subject to change as the oil is disturbed or becomes heated from response activities (shelter, flushing, etc.). Previously metered areas whose atmosphere was measured below hazardous levels could become hazardous again as the oil is disturbed and/or heated. Continuous monitoring in the area workers will be present is the best practice.

Moving Water: As mentioned in Section 2.2, river ice is less predictable than lake ice due to fluctuating water levels, under-ice currents, and varying bottom conditions. River ice is generally weaker, and changes in water levels can leave ice unsupported, creating air voids underneath that increase the risk of breakthrough. Additionally, moving water poses significant dangers to responders who may fall in:

- Ice provides little traction, making it difficult to hold on.
- Strong currents can pull responders under the ice.
- Moving water can propel responders into ice edges or impact them with floating ice.

A rescue plan should be included in the ice safety plan and, if necessary, rescue teams should be placed on standby. Responders working on unstable ice should be equipped with the following (Figure 3-5):

- Harness and Rope: Responders should wear a life jacket with a harness attached to a securely anchored rope in a profiled or safe area. Climbing ice screws are effective anchors when securing ropes in ice.
- Ice Awls: A simple and cost-effective tool that assists in self-rescue and helps resist the force of moving water.
- Throw Bags: Enables rescuers to assist someone who has fallen in without getting too close to compromised ice.

Refer to Figure 3-2 for additional recommended PPE.

Responders should be trained in basic self-rescue techniques (Figure 3-5). If a responder falls into moving water, they should remember the 1-10-1 Principle, developed by Dr. Gordon Giesbrecht, a leading expert in hypothermia:

1 — Cold Shock: You have one minute to stay calm and control your breathing to prevent gasping and inhaling water.

10 — Cold Incapacitation: You have about 10 minutes of meaningful movement before muscle function declines due to the cold. Use this time to self-rescue or secure yourself.

1 — Hypothermia: Unconsciousness due to hypothermia can occur in approximately one hour, depending on water temperature and personal protection.

Understanding these phases helps individuals improve their chances of survival by focusing on controlled breathing, self-rescue, and delaying the onset of hypothermia. When attempting self-rescue, exit the water toward the strongest part of the ice. The safest exit point is usually where you fell in, as this area previously supported your weight up to the moment of breakthrough.

For additional information on cold-water immersion, the U.S. Coast Guard Auxiliary provides resources at: https://wow.uscgaux.info/content.php?unit=095-43-04&category=cold-water-immersion

Figure 3-5. Clockwise from top left. Ice screw in ice block. These can be used as a safety anchor. Using a throw bag to help recover a person while staying on safe ice. Ice awls used for self-rescue. Ice awls close up. Photos: ACS.

Ice and cold water diving is hazardous due to extreme environmental conditions, requiring specialized equipment, procedures, and training. Awareness of environmental factors, proper planning, and logistical support are critical for safety and operational success. Diving in ice environments requires certified, experienced surface-supplied commercial divers using equipment designed for cold water environments. Scuba diving should not be permitted for oil spill response and commercial ice diving operations. All commercial diving operations should meet or exceed Association of Diving Contractors International (ADCI), USCG, and the Occupational Safety and Health Administration (OSHA) standards and regulations. The U.S. Navy, National Oceanic and Atmospheric Administration and other diving organizations also published guidelines for conducting diving operations below the ice.

The following checklist summarizes recommended ice diving best practices:

- ☐ The diving crew must meet ADCI, USCG and OSHA standards and regulations. FOSCs should complete the commercial diving checklist found in API Report 1154-1, dated 2016, USCG Diving Program Manual COMDTIINST M3150 series, and coordinate diving operations with the District Response Advisory Team.

- ☐ A written diving safety plan must be prepared in advance of ice diving operations that addresses site conditions, ice access, entry/exit points, environmental conditions, diver thermal protection, emergency medical care, the nearest decompression chamber, planned dive profile, and emergency procedures, among other safety concerns.

- ☐ The minimum dive crew will require five members, including a diving supervisor, primary diver with tender, and standby diver with tender.

- ☐ Divers must wear adequate thermal protection, such as a dry suit or, ideally, a hot-water diving suit. Suits must always be checked for damage prior to entry. All divers must be monitored for signs of cold stress or hypothermia.

- ☐ Regulators should be kept warm, tested before use, and handled carefully to prevent freeze-up. Kirby Morgan recommends a hot-water shroud for regulators in waters below 34°F and notes the greatest risk of regulator icing occurs on the surface when air temperatures are below 32°F. Moisture-free air should be supplied for bailout bottles and other cylinders.

- ☐ Shelters or windbreaks should be erected near the dive site to protect divers and equipment from freezing. Divers should always have ready access to a warm shelter following diving operations.

- ☐ Entry holes should be cleanly cut, marked to prevent accidents, and remain open throughout the operation. Escape holes are required in areas with currents. Note, ice movements pose significant risks and can close access holes may damage an umbilical.

4 Logistics and Support

4.1 Logistical Support Equipment

Oil spill operations on ice require sufficient supplies that must be readily available near the response site. Delivering these supplies typically involves support equipment to transport them to the operational area. Given the varied and dynamic nature of ice conditions, the type of equipment used must be adaptable to ensure safe and efficient logistics (Figure 4-1). First and foremost, the ice must be capable of supporting the equipment used for logistical support, as outlined in Section 2.5. Lightweight equipment or options that distribute weight effectively are often preferred. These may include snowmobiles with sleds, Rolligons, and small ATVs with tracks.

In areas with thin or broken ice, equipment should be capable of operating both on the ice and in water with broken ice. This equipment should also provide a safe platform for responders to work from, including options such as jon boats and airboats. Many amphibious vehicles are particularly effective in these conditions, as they can navigate the diverse challenges of on-ice operations. Examples include hovercraft, ice-capable airboats such as the Husky, and specialized vehicles such as the SHERP.

Helicopters can also play a role by transporting personnel and equipment to remote locations, laying boom near deployment areas, and serving as a work platform while hovering over ice for tasks such as ice profiling.

Access methods for on-ice operations include john boat, equipment capable of transiting on thin ice and transitioning from water to ice and vice versa (e.g., AIR responder), sleds, hovercraft, helicopter, airboat, snow machines, amphibious vehicles such as SHERPs, etc. (Figures 4-2 and 4-3).

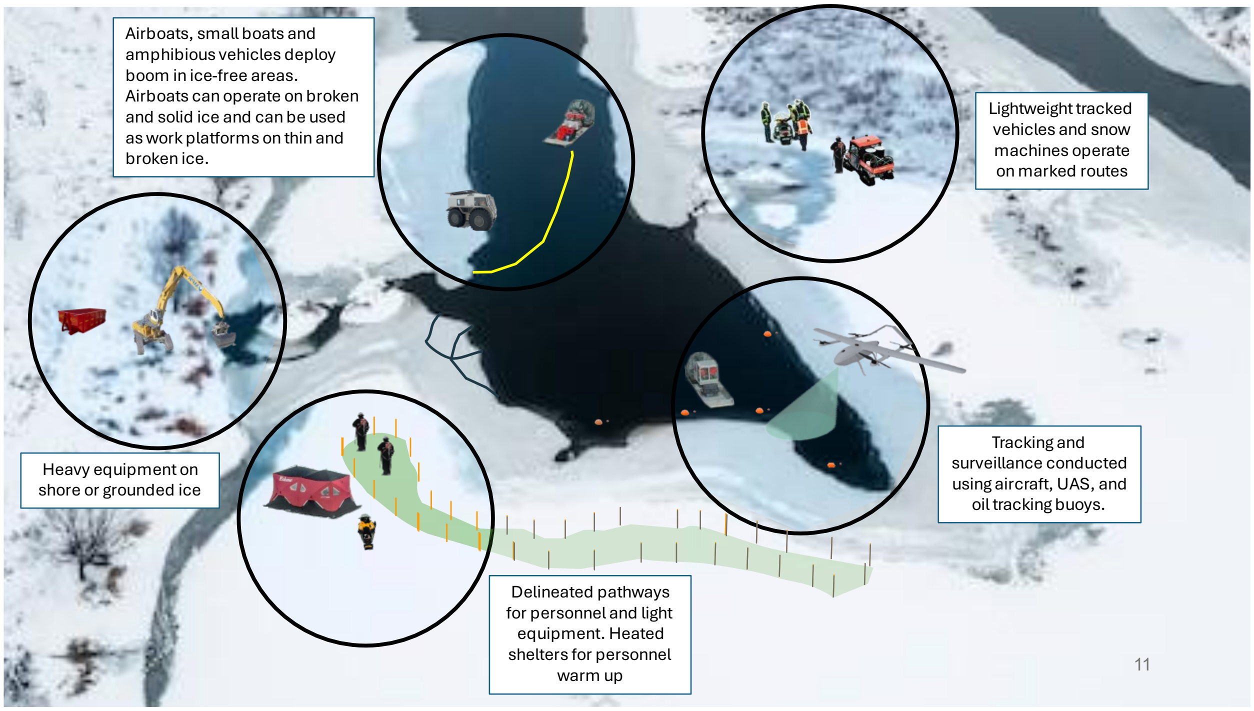


Figure 4-1. Access methods for on-ice operations, highlighting designated travel routes for specific equipment based on ice conditions and guidelines outlined in Section 2.5. Credit: ACS.


Figure 4-2. (Left) Rescue hovercraft during a training exercise https://www.neoterichovercraft.com/hovercraft-gallery/gallery.php?section=main&gallery=rescue#images-8. (Right) Helicopter sling loading boom to remote area for deployment. Photo: ACS.

Figure 4-3. Examples of airboats and amphibious vehicles used to access areas of water and thin ice. Clockwise from top left, SHERP, Kubota ATV with tracks, airboats (open and closed cab), and Husky airboats. Photos: ACS.

4.2 Ice Road and Pad Construction and Maintenance

As discussed in Section 2.5, there is a very low probability of being able to construct or use ice roads in the Great Lakes; however, some considerations for when they might be part of a response are provided.

An ice road is constructed by spraying water from a source—such as a water truck or drilled holes through ice into the water body—onto the freezing surface of a waterbody or land. This water is applied in layers, freezing incrementally as additional water is added. The thickness of the ice road is determined by the type of equipment that will travel on it and the underlying terrain. To provide access off the pad or road, an ice ramp is constructed, which requires a greater thickness than the road itself.

4.3 Sustaining Field Operations in Remote, Cold-Weather Conditions

Sustaining remote field operations in cold weather revolves around two primary focuses: sustaining personnel and sustaining equipment. Both are essential to ensuring effective and continuous response operations.

Sustaining Personnel

Shelters: All personnel should have appropriate PPE to stay warm and prevent cold-related conditions such as hypothermia and frostbite, as outlined in Section 3. However, PPE should be considered a tertiary safeguard; primary means of protection (engineering and administrative controls), such as adequate shelter and heat sources, should always be available.

Shelters should provide protection from wind, snow, and rain while offering warmth. They come in a variety of sizes and features to suit different operational needs (Figures 4-4 and 4-5):

- **Small, mobile shelters** – Ice fishing tents or enclosed snowmobile sleds provide a windbreak and heat retention while remaining highly portable.
- **Intermediate shelters** – Wall or lodge-style tents offer a balance of space and portability, allowing for quick setup and breakdown.
- **Larger, mobile shelters** – Engineered fabric-on-frame structures, such as Weatherports or air-frame shelters such as Zumro, provide longer-term solutions while remaining lightweight and portable.
- **Towable shelters** – Mounted on wheels, tracks, or skis, these steel-framed structures are better suited for use on shorelines, staging areas, or thick, stable ice due to their higher weight and durability.

Figure 4-4. Ice fishing tents and enclosed snow mobile sleds offer small, mobile, shelter options. (Photos: Left, ACS. Right, Equinox Industries Ltd., https://eqnx.biz/product/snowcoach-mpv/).

Figure 4-5. (Left) Large shelter options airframe structures include the Zumro. Photo: ACS. (Right) Fabric on frame shelters can be used (https://alaskastructures.com).

Heat: Shelters should have access to a reliable heat source to allow personnel to warm up and maintain operational effectiveness in cold conditions. Heat sources, like shelters, vary in size and capability to suit different operational needs (Figure 4-6).

Figure 4-6. Heat options clockwise from top left. Propane heater (Mr. Buddy), industrial indirect fired heater (ES700), propane-fired shelter heater (Zumro), portable diesel air heater (Planar).

Small-Scale Heating Solutions

- Propane heaters (e.g., Mr. Buddy heaters) and portable diesel forced-air heaters (e.g., Planar heaters) are ideal for mobility and small shelters such as ice fishing tents or enclosed snowmobile sleds.
- Diesel forced-air heaters are highly efficient, often running for 12-18 hours on a single gallon of fuel.

Medium to Large Heating Solutions

- Higher BTU propane and diesel-fired heaters provide more substantial heat output for larger shelters.
- Portable wood stoves offer an alternative heat source where fuel availability and weight limitations allow.
- Industrial indirect-fired air heaters, when weight and access permit, can produce significant heat output suitable for large shelters and equipment heating.

In cold-weather conditions, fuel sources such as diesel can gel, and propane can condense at extremely low temperatures. More commonly, propane systems experience component icing, which can prevent fuel from reaching the combustion area. To mitigate these issues, anti-gel additives can be used for diesel, and propane tanks and components can be insulated and periodically rotated with warm tanks. Care should be taken that heat sources do not introduce carbon monoxide into the shelter.

Lighting: Both interior lighting for shelters and exterior lighting for work areas are crucial for safety. Options include flashlights, headlamps, light bars, battery-powered light plants, LED strips, LED plastic tube lamps, and floodlights (Figure 4-7). These can be powered by batteries and/or generators.

Figure 4-7. Clockwise from top left. Plastic LED tube lamp in Zumro, battery-powered light bar on snow mobile coach exterior, flood lights on tracked trailer with generators, and Pelican remote area battery powered light plant. Photos: ACS.

Power: Generator power is typically the most reliable and easily supported option in remote areas. Battery-powered “generators” or components can also be used but should be considered short-term or transitional solutions, primarily for site setup or initial response periods.

- Small generators (up to 2000 W) are highly portable and can run for approximately 8 hours.
- Medium generators (around 3000 W) remain mobile and can be moved by personnel. They support larger loads and may run up to 18 hours, depending on the manufacturer and load; higher loads result in shorter runtime.
- Large generators (6000 W or more) can weigh nearly 200 pounds and require additional support for safe transportation. These units typically run for about 6-8 hours.

Gas-powered generators generally perform well in cold temperatures. However, in extreme cold or during prolonged operations, periodic cycling into “an equipment warm-up area” may be necessary. Generators and fuel tanks should always be stored in secondary containment when used on ice to prevent environmental contamination.

Food and Water: In cold-weather conditions, it is essential to keep personnel well-fed and hydrated. Food provides the necessary calories to generate body heat, while hydration helps prevent cold-related injuries such as hypothermia and frostbite. In addition to their physiological importance, resources like food, water, heating, and lighting play a crucial role in maintaining responder morale and overall effectiveness during operations.

Waste Management: Waste streams at remote sites may include both food waste and oily waste, each of which should be collected, stored, and disposed of in accordance with the incident waste plan and applicable laws and regulations.

- Waste should be stored securely to prevent attracting wildlife and to restrict animal access.
- If stored outdoors, the area should be well-lit to deter wildlife.
- Oily waste should be kept separate from other waste.
- Waste containers should be clearly labeled to indicate the type of waste they contain.

Whenever possible, return trips from remote sites to primary staging areas or populated regions should include waste transport to ensure proper disposal.

Sustaining Equipment

Many of the requirements for equipment mirror those for personnel. Responders should have a sheltered area to maintain equipment, which can initially be the same shelter used for personnel during short-term or early response phases. Additional shelter options include parachutes or plastic sheeting that can be placed around equipment as needed and secured with timbers, snow, or climbing ice screws (Figure 4-8).

Heat sources for equipment remain similar to those used for personnel; however, heaters that produce carbon monoxide may be considered if operated outdoors and away from personnel.

<u>Equipment Maintenance</u>: Maintaining equipment at remote cold-weather sites relies on preemptive planning and scheduling. In addition to routine maintenance tasks such as oil changes and fueling, planning for warm-up cycles helps ensure continuous operations. For example, when using a generator, a spare should be kept in a warm area, fueled, and ready for use. When the primary generator requires refueling, it can be swapped with the spare, allowing time for fueling and maintenance checks in a warm environment. While these steps may not always be necessary, they should be considered if equipment failures occur frequently in cold conditions.

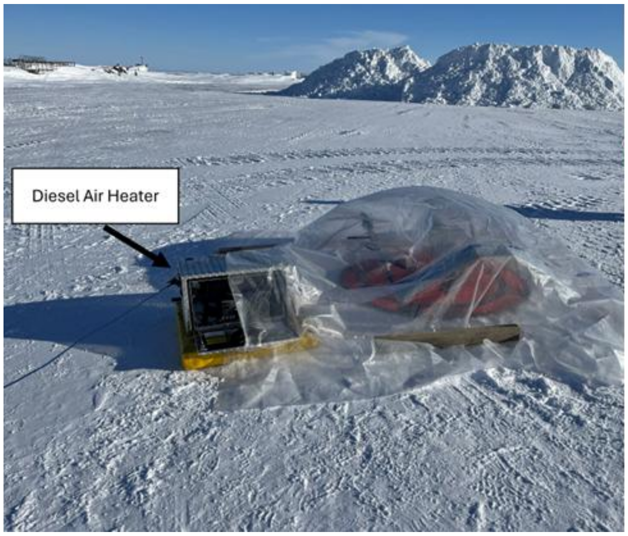


Figure 4-8. (Left) Reinforced plastic sheeting placed over a drone and held down by timbers to keep batteries and internal components warm between flights. Heat source is a diesel air heater. (Right) Battery-powered auger. Photos: ACS.

Much of the recovery equipment operates at the oil-water interface, making it prone to icing and freezing. To address this, heat sources should be available, and equipment rotation strategies should be considered. For instance, chainsaws used for slotting may experience chains freezing to the bars between uses. These can be stored in a warm shelter, placed in a heater trunk for thawing, or rotated with a spare.

Battery Equipment: Battery-powered equipment is increasingly common and offers viable alternatives to traditionally powered tools. Common examples include tools, lights, pumps, heaters, and augers (Figure 4-8).

Battery-powered equipment provides several advantages for remote site operations:

- Typically lightweight and easier to transport.
- Eliminates the need for fuel, reducing spill risks.
- Simplifies operation in cold temperatures with easier startup.

For sustained use, a reliable method to recharge batteries should be in place. Cold temperatures can significantly reduce battery performance and their ability to hold a charge. To mitigate this, extra batteries should be kept on hand and stored in a warm area to ensure availability when needed. If indoor warm storage is not feasible, then a small portable warm shelter should be used to minimize depletion and potential damage to batteries and equipment.

Additional strategies for managing ice formation on equipment and at the site are covered in Section 6.1.

Securing Equipment: Strong winds can displace shelters and other lightweight materials, making proper anchoring essential. On ice, anchoring can be effectively achieved using climbing ice screws (Figure 4-9) and rope. Carabiners can also be useful for securing lines; however, it is best to avoid double-locking or screw-type carabiners, as ice buildup can make them difficult to operate. To further secure shelters, burying the edges in snow helps prevent wind from entering and lifting the structure, while also enhancing heat retention.

Figure 4-9. Clockwise from left. Zumro Tent with anchor line attached. Ice screw being used as an anchor. Buried edge of ice fishing tent. Photos: ACS.

Available communication options include:

- Cellular hotspots and gateways – Provide connectivity in areas with cellular coverage. These can see reduced bandwidth depending on provider and usage.
- Satellite internet (e.g., Starlink) – Offers high-speed connectivity with minimal logistical support, making it one of the best options for remote site data links.
- Microwave datalinks – Suitable for establishing dedicated high-bandwidth connections between fixed locations. Line of sight is required.

5 Oil Detection, Mapping, Tracking, and Weathering

To mount an effective spill response, it is critical to know where the spilled oil is at any given time, the boundaries of the contaminated area, and a prediction of where the oil is likely moving to under the influence of wind and currents. Ideally, any winter surveillance program aimed at locating the oil will also provide an indication of ice concentrations, likely oil thickness and degree of oil weathering as a guide to responders in safely and effectively deploying different response tools such as mechanical recovery or ISB. In the absence of direct sampling, oil fate and behavior models can provide a guide as to the expected oil properties such as degree of emulsification and viscosity.

Information is obtained by using a combination of surveillance (relying heavily on remote sensing with aerial and under water sensors), tracking beacons deployed among ice floes or on the ice surface, and trajectory modelling (see Sections 5.1 and 5.2). The presence of lake ice greatly increases the complexity of detecting, mapping, and tracking but there are tested and proven solutions as covered in the following subsections.

Comprehensive tracking and long-term monitoring of oil released in ice requires assimilating field data, plotting real-time observations, and integrating this information with forecasting tools such as weather models, ice drift algorithms, and oil spreading and weathering models.

5.1 Detection and Mapping Techniques

There are a number of options available to detect oil under ice depending on conditions and resources: electric or gas power head augers, underwater lights, GPR, acoustic sensors (sonar), optical sensors including Infrared mounted on Remotely Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs), Uncrewed Aerial Systems (UAS), helicopters, and fixed-wing aircraft. Recent successful field trials show how oil detection canines can detect oil under ice (Figure 5-1).

Figure 5-1. The challenge of oil and ice detection and mapping portrayed by the mix of different sensors and platforms required to cover a wide range of oil in ice scenarios (Owens and Dickins 2015).

Early research on spill detection in ice began 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, gas sniffers, and airborne and ground-based penetrating radar (e.g., Dickins 2000; Fingas and Brown 2014).

Drilling a pattern of holes is the simplest, albeit extremely labor-intensive and highest risk means of finding and mapping the extent of oil under ice. This technique is only practical for relatively small areas (hundreds of feet in extent) nearshore where the likely location of the oil is already known and crews can safely go out onto a stable ice cover (Section 3). In the case of larger spills spread over a wider area and in unstable, mobile ice offshore, it will be necessary to employ some form of remote sensing.

Determinations of which sensors are most likely to succeed in different oil in ice scenarios was extrapolated largely from experiences with temperate spills (e.g., Leifer et al. 2012), supported by a small number of field tests and tank/basin experiments. The SINTEF Oil in Ice JIP (Dickins and Anderson 2009; Sørstrøm et al. 2010) summarized the state of the art for remote sensing of oil in ice with a number of key points that remain largely valid today:

- A mix of conventional airborne sensors in current use will likely prove effective with spills in relatively open ice cover (1/10 to 4/10).
- The use of existing remote sensing systems to detect spills contained on the surface among closely packed ice is still largely unknown.
- The detection of oil underneath and trapped within the ice remains a major challenge.
- Future platforms will likely include both UAS and AUV carrying a suite of sensors.
- Trained human observers remain an essential element of any surveillance program, and the best means of avoiding or reducing the number of false positives where oil is visible on the surface.

The most comprehensive comparison of different sensors in detecting oil under ice and trapped within ice, took place at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) in 2015 (Pegau et al. 2017). Key findings from the CRREL test basin experiments are summarized as:

- The project confirmed the overall conclusion of previous work, that while all sensors showed an ability to detect oil on, in, or under ice under certain conditions, no one sensor has the capability of detecting oil in all situations. Some sensors may complement each other in terms of oil thickness resolution vs. area coverage or swath width.
- Future operational systems will likely employ suites of different sensors operating from various platforms under, on, and above the ice surface to detect oil in a range of ice environments at different times of the year.
- An effective underwater detection suite should have a low light camera, broadband and/or multibeam sonar, and possibly a spectral radiometer or Fluorescence Polarization (FP). While the various sonar units showed similar levels of capability in detecting oil under and in ice, the multibeam type of sonar provides the added ability to create a 3D map of the underside of the ice that may help identify priority locations for oil to accumulate and narrow the search area (oil will naturally seek the highest spots in the under ice surface – thinnest ice).
- The study results suggest that aerial sensors should include visible and thermal infrared imagers.
- Existing commercial GPR systems operated from the surface are capable of detecting oil trapped within ice.

The matrix in Figure 5-2 summarizes the findings of the CRREL ice basin tests and modelling predictions.

The following sections highlight the state of knowledge for several key sensors and platforms.

Platform	Airborne				On-ice		Below Ice		
Sensor	GPR	Optical	FP	IR	GPR	ODC	Optical	FP	Acoustic
Exposed oil on ice	N/A	Green	Green	Yellow	N/A	Green	Yellow	N/A	N/A
Snow covered oil on ice	Green	Red	Red	Red	Green	Green	Yellow	Red	Red
Oil under thin lake ice <~10 cm	Yellow	Red	Red	Red	Green	Green	Green	Yellow	Green
Oil under thicker lake ice	Yellow	Red	Red	Red	Green	Yellow	Green	Yellow	Green
Oil encapsulated by new ice	Red	Red	Red	Red	Yellow	Yellow	Yellow	Red	Yellow

Figure 5-2. Expected field performance of sensors tested in the 2015 ice basin experiment. Green = Likely; Yellow = Has Potential; Red = Not Likely; NA = Not applicable.

Performance Colors: Performance rating GREEN indicates a high likelihood of effectiveness based on previous tank/basin/field testing. YELLOW indicates that there are conditions that may allow the system to work, and others when it is expected to fail. In some cases, this rating is assigned because of insufficient data to fully assess performance. RED indicates a low likelihood that a sensor would prove effective. N/A – not applicable (e.g., you would not deploy a GPR to look for visible oil on the surface or below ice sensors to detect oil on the surface).

Figure Notes:
The CRREL research project and previous studies on oil detection in ice have focused on crude oil rather than other relatively colorless petroleum products like gasoline or diesel. Without the clear contrast between black oil and white ice, it could be difficult to visually locate a spill in ice, especially in low light conditions. Optical and IR systems may not achieve the same detection as they did when testing on crude oil – for example, a diesel or gasoline spill may not exhibit the same temperature rise as solar absorbing crude oil. Oil detecting canines may do better with products having more light ends. The differences in individual detection capability with different oils is largely unknown.
GPR – Ground Penetrating Radar; Optical – low light cameras; **FP** – fluorescence polarization (laser fluorosensor in aircraft); **IR** – Airborne Infrared; **ODC** – Oil Detecting Canine; Acoustic (Sonar)
Airborne – requires a suitable platform (aircraft or UAS) and good flying weather including light winds for drones and Visual Flight Rules (VFR) for manned aircraft.
On ice – sensors require sufficient thickness for safe deployment of personnel, equipment and canines – as an example, the Michigan State Department of Natural Resources call for a minimum of 4 inches for ice fishing, walking, skiing on lake ice.
Below ice – requires suitable platforms such as Autonomous Underwater Vehicles (AUVs), or Remotely Operated Vehicles (ROVs requiring a tether). These platforms need a minimum of 10 ft water depth below the ice to operate comfortably and ~8 inches ice to provide a safe working platform for transporting, cutting access holes, and retrieving.

Radar: GPR is an effective tool for quickly profiling freshwater ice thickness and determining whether the ice is safe to deploy work crews (see Section 2.5). Most importantly, GPR is the only surface sensor that has a demonstrated ability to detect oil trapped beneath or trapped within a solid ice sheet (Dickins et al. 2008). In theory, GPR should be much more effective in detecting oil underneath or trapped within fresh-water ice than in sea ice; warm, salty ice greatly attenuates the radar signal.

Airborne GPR could prove valuable in situations where oil is buried under snow on the ice surface. A portable, lightweight commercially available GPR suspended beneath a helicopter traveling at speeds up to 20 knots and altitudes up to 60 ft, successfully detected a thin layer of crude oil buried under hard-packed snow during field tests on Svalbard (Bradford et al. 2010).

The main limitations of GPR are the difficulty in interpreting the results without trained personnel, the need for a relatively uniform ice cover, and the need for crews to work safely from the ice surface (Dickins et al. 2008).

Infrared Systems: Infrared (IR) systems are a primary sensor used worldwide for detecting oil slicks on open water from low-flying aircraft and surface vessels. Oil among or on ice absorbs solar radiation and heats up faster than its surroundings, often leading to sufficient temperature difference from the unoiled surroundings to provide positive detection. Airborne IR sensors are used operationally in Alaska for spills on land.

A large-scale experimental release of oil in pack ice in Norway in 1993 demonstrated that a simple IR video camera in a helicopter clearly detected warm oil being pumped by hose over colder ice and then into the water between floes (Vefsnmo and Johannessen 1994). Multi-spectral and thermal IR cameras were used successfully to detect, map and estimate thickness of slicks during the *Deepwater Horizon* incident (Leifer et al. 2012). Ship-based IR sensors were successfully delineated oil trapped between floes in close pack ice during an experimental spill (Dickins and Andersen 2009; Sørstrøm et al. 2010). Systems that integrate high-resolution Forward-Looking IR (FLIR) and low-light video (LLTV) are deployed on several Norwegian and U.S. offshore response vessels but remain untested with spills in ice. Figure 5-3 shows an IR image of oil on ice in a test tank, clearly distinguishing the warm oil from the colder clean ice and structures.

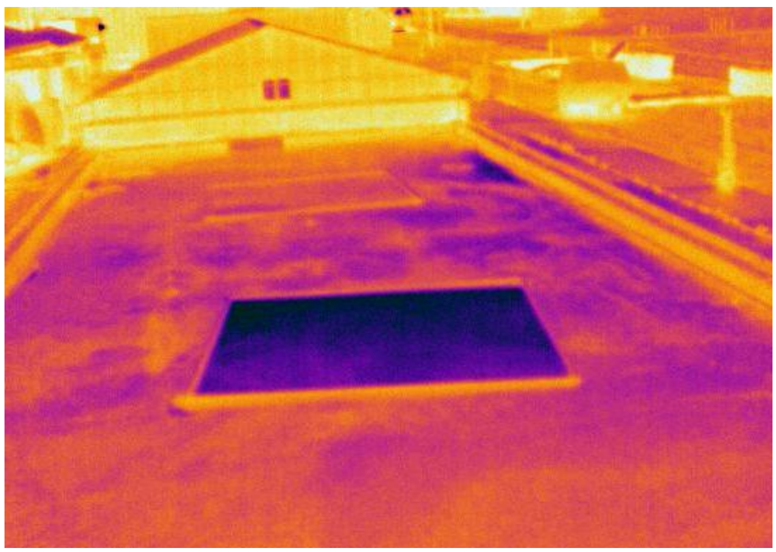


Figure 5-3. IR image of oil spilled onto an ice sheet in the CRREL outdoor basin (Pegau et al. 2016).

<u>Oil Detection Canines</u>: Contingent on safety (e.g., ice floe size, thickness, stability) trained dogs with their handlers can track and locate even very small oil spills buried under snow from long distances. In trials on Svalbard in 2008, dogs successfully detected a small quantity of oil buried under snow on the ice surface from a downwind distance of 3 miles (Brandvik and Buvik 2009). In February 2025, a trained oil detection canine successfully located several different oil types (diesel, condensate, heavy crude) deliberately placed under lake ice in Canada (IISD 2025).

<u>Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs)</u>: Field trials off NE Greenland more than a decade ago demonstrated the ability of AUVs to carry sensor packages over long distances beneath sea ice (Wadhams et al. 2006). More recently, single- and multi-beam sonar sensors successfully detected and mapped the boundaries and thickness of oil spilled under ice in basin tests at the CRREL facility in Hanover, NH (Wilkinson et al. 2015). Known drawbacks with using underwater AUVs to look for oil under ice include relatively slow survey speed (compared to aerial platforms), inability to transmit large volumes of real-time data such as imagery to the surface, and positioning under moving ice. Proven ROV technology avoids the data transmission and positioning issues, but at the cost of being tied to the mother ship by an umbilical cord, limiting the survey range.

Hansen and Fitzpatrick (2018) present the results of a series of annual shipboard deployments in the Arctic and the Great Lakes testing a variety of systems including UAVs and ROVs. An ongoing (2025) study funded by the U.S. Bureau of Safety and Environmental Enforcement (BSEE) carried out a series of test programs to test and evaluate different underwater sensors (optical, irradiance, and sonar) for their ability to detect oil under ice as well as submerged oil on the bottom. During that program, trials in 2024 at the CRREL facility and the Ohmsett test basin showed that a combination of acoustic (sonar) and optical sensors can not only detect oil under ice but also provide some information about the film thickness (report in preparation).

Uncrewed Aircraft Systems (UAS): UAS technology was in its infancy at the outset of the JIP. Groups in Alaska and elsewhere were considering UAS as potential future surveillance platforms in polar regions. For example, beginning in 2012, the USCG incorporated UAS tests as a key element in their annual "Arctic Shield" and Great Lakes deployment exercises to develop response strategies and logistics platforms for oil in cold water and ice response (Hansen and Fitzpatrick 2018. Since that time, the capabilities and operational uses of UAS have expanded exponentially to the point where these systems should be considered as a primary surveillance tool to collect high-resolution imagery of any nearshore spill site. For spills into ice where the oil is on the surface contained between ice floes, aerial video or photography with UAS can provide a rapid georeferenced record of location and oil extent. Limitations center around high winds, periods of low visibility and securing FAA approvals for Beyond Line of Sight operation.

Dedicated Pollution Surveillance Aircraft*:* Arctic nations such as Canada, Denmark, Finland, Iceland, Norway, the U.S., and Sweden all operate dedicated pollution surveillance aircraft. The sensor suite on-board these aircraft was generally selected based on known capabilities in open-water pollution surveillance. Little or no data are available to determine individual airborne sensor capabilities or operating windows in responding to a spill in ice. Leifer et al. (2012) provided a comprehensive evaluation of airborne sensors in the context of open-water spills such as the *Deepwater Horizon*. Many of their conclusions are likely applicable to spills in open drift ice (40-60% ice coverage) where large patches of oil are visible, trapped between floes.

In 2017, the USCG upgraded their fleet of C-27J Spartan medium-range surveillance aircraft with electro-optical infrared (EO/IR) sensors. The high-definition EO/IR sensors were also installed across the USCG other fixed-wing platforms: the HC-144 Ocean Sentry medium-range surveillance aircraft and HC-130J Super Hercules long range surveillance aircraft. The USCG completed a refresh of all 18 aircraft in the fleet in September 2024, integrating two significant upgrade projects: 1) Ocean Sentry upgrades the aircraft with a new flight management system, which serves as the primary avionics computer for communication control, navigation and equipment monitoring; and 2) Minotaur missionization integrates installed sensors (including high-resolution, forward looking IR) and radar and provides dramatically improved data fusion as well as information processing capabilities. The modifications to the HC-144B enables crews to fly with lower cloud ceilings, allowing on-scene coverage to continue in marginal conditions. These aircraft could greatly assist in surveillance and detection for a Great Lakes spill response in ice or open water.

5.2 Tracking Oil Movement

The goal of operational oil spill modelling is to provide answers to four basic questions: 1) Where is the oil being transported? 2) When will it get there? 3) What will it look like, i.e., degree of weathering; and 4) Will it be in recoverable quantities?

Some key points to remember regarding oil movement in the presence of ice:

- 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.

Oil trapped under solid, stable ice (e.g., from a pipeline release or sunken vessel) can move laterally under the ice given enough current. This is more likely in narrow straits or rivers than open lakes. Previous research in test tanks determined that the threshold velocity needed to initiate and sustain movement ranged approximately from ~15 cm/sec (0.3 knots) under smooth ice to ~ 21 cm/s (0.4 knots) under slightly rougher ice (Buist et al. 2009). Currents of this order of magnitude could occur in many areas. Once the oil begins moving, it's velocity will vary according to the ice roughness and oil viscosity, with lighter oils moving faster.

Oil trapped within pack ice over 6/10 concentration (60% ice coverage by area) 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 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 between the oil and ice, depending greatly on the ice freeboard and roughness (acting like a sail).

Figure 5-4, based on data from an actual experimental spill in ice, shows how oiled ice can move large distances, tens of miles, in a short period of time during storm events.

Recognizing that even the best forecast models (oil spill, weather, etc.) will produce even larger error bounds after days and weeks, it becomes necessary to reinitialize the oil spill models on a frequent basis (tens of hours to days) with the most accurate real-time spill coordinates available, for example using satellite imagery, airborne surveillance data, or GPS tracking buoys, and updated wind and ocean current forecasts.

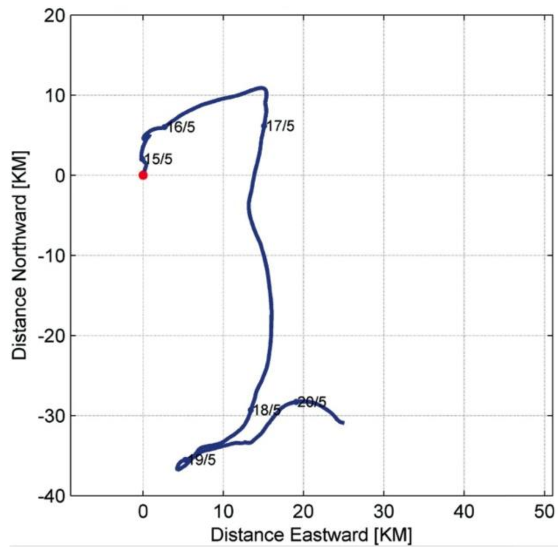


Figure 5-4. Actual oil in ice drift track from the 2009 SINTEF oil in ice JIP experiment in the Norwegian Barents Sea. Note the 19 nautical mile southerly displacement on May 18 during a period of sustained wind speeds over 29 knots. The drift rate closely matched the general rule of thumb at ~ 3% of wind speed (Sørstrøm et al. 2010).

GPS buoys can be deployed in oil slicks within broken or forming ice, floating with the oil and reporting its location. In areas of forming ice that later solidifies, ice-hardened GPS buoys can be positioned to freeze into the ice pack, allowing them to move with the oiled ice. With ice coverage equal to or greater than 60% (6/10), the beacons will effectively track the oiled ice motion as the oil tends to move with the ice in these close pack conditions. To track oil under ice, threshold velocities from previous extensive laboratory tests can be used to predict the extent of oil movement with different current speeds.

Commercially available ice-strengthened GPS beacons and buoys have routinely tracked ice movements during an entire winter season throughout the polar basin for decades. In the event of continuous release over time (e.g., a leaking vessel), deploying beacons at regular intervals as the oiled ice moves away from the spill source will generate a close to real-time track of the oil location. The GPS positions can then be used to direct responders to the spill. Closely spaced GPS beacons can also follow the evolving pattern of spill fragmentation and divergence as the pack expands and contracts. Figure 5-5 shows an example of a GPS ice tracking buoy designed to survive in thick, rough ice in the Arctic Basin. Simpler, more economical oil tracking buoys can work, but they are not designed to resist the high-pressures of the ice and may have a short life in a highly dynamic ice environment with ridging and rubble actively forming.

A 2024 study looks at the challenge of modelling oil spill transport in the Great Lakes with an ice cover present (Song et al. 2024). The researchers developed a prediction system for oil with ice modeling by coupling the General NOAA Operational Modeling Environment (GNOME) model with the Great Lakes Operational Forecast System (GLOFS) model. Taking Lake Erie as a pilot study, they used observed drifter data to evaluate the performance of the coupled model. The study developed six hypothetical oil spill cases in Lake Erie, considering both with and without ice conditions during the freezing, stable, and melting seasons spanning from 2018 to 2022, to investigate the impacts of ice cover on oil spill processes. The results showed the effective performance of a coupled model system in capturing the movements of a deployed drifter. Through simulations, it was observed that the stable season with high concentrations of ice had the most significant impact on limiting oil transport compared to the

Figure 5-5. Positioning buoy deployed on Arctic Sea ice. Photo: Alfred Wegener Institute/Mario Hoppmann.

freezing and melting seasons; with significant ice cover, the oil- affected open water area was only 7 square miles after 5 days, while without ice cover, the spill area reached 71 square miles – a factor of 10x larger.

In 2016, the University of Michigan's Water Center conducted a comprehensive study to assess the potential impacts of an oil spill in the Straits of Mackinac, focusing on Enbridge's Line 5 pipeline. The study utilized advanced computer simulations to predict the behavior and consequences of hypothetical oil spills in this critical area, using an approach similar to NOAA’s GNOME model.

5.3 Oil Weathering and Fate

Weathering and spreading of oil in the presence of ice is significantly different from those processes in more temperate waters (Dickins 2011). Weathering of oil in sea ice has been studied extensively in a number of comprehensive research efforts in Norway and the U.S. (Buist et al. 2009; Brandvik and Faksness 2009; Sørstrøm et al. 2010). This extensive knowledge base on oil fate and behavior in ice is now incorporated in commercially available models such as OSCAR and OILMAP in common use throughout the oil spill response community.

While the current generation of oil spill models can predict the behavior of oil and its likely weathering fate in ice environments (e.g., degree of evaporation, rate of emulsification, etc.), they have limited capabilities to realistically model close to real-time oil movements in the presence of a significant ice cover during an actual response. This deficiency derives from two main problems: 1) the limited resolution offered by the existing ice models; and 2) the inability of the existing oil spill trajectory models to efficiently import and process data from ice models. The IOGP Arctic Response Technology JIP aimed to overcome some of the known deficiencies in modelling oil movements in ice (Beagle-Krause et al. 2017).

Coordination is the key to successful use of the ice model data with the oil spill trajectory models. Missing any data component (i.e., currents, ice and wind) in the transfer creates unnecessary problems that can stretch available personnel resources, especially during an actual incident where limited time is available to bring the modelling team up to full operational status.

6 Tactics for Different Oil in Ice Scenarios

6.1 Introduction: Systems Approach to Oil Spill Response

Responders in the Great Lakes have a suite of proven response tools available for marine operations in both open water and ice (mechanical recovery, removal through in situ burning, and where recovery is not practical or possible, monitoring/natural recovery). There are clear differences in operational limits for each oil spill response strategy based on wind, waves, temperature, and ice concentration. Each response method has certain advantages (e.g., speed, efficiency, simplicity), and potential disadvantages from operational or environmental perspectives (e.g., soot and residue from in situ burning; low encounter rates for containment and mechanical recovery in ice, large volumes of oily waste etc.).

At an operational level, the choice of which response option is optimal or recommended in any given situation goes beyond simply how much oil responders can remove in specified time. It depends on a complex set of factors such as:

- Type of oil spilled;
- Locations of response equipment and logistics;
- Environmental resources and habitats at risk;
- Social and cultural sensitivities such as subsistence harvesting and commercial fisheries, ice weather and sea state conditions;
- Degree of oil weathering;
- Availability of logistical and operational support including tracking and monitoring; and
- The ability to secure necessary state permits and agency approvals in a timely manner. Mechanical recovery can proceed without approval or permits in most cases but in situ burning may require sign off at various Federal and State levels.

Ideally, the response team can apply the different oil spill response options as an integrated system, whereby different countermeasures work together concurrently in a complimentary manner, for example, directly burning naturally thick patches of oil trapped among concentrated ice while at the same time booming and skimming oil in more open drift or pack ice nearby. In some cases, the addition of mixing energy from vessel propeller wash can disperse fresh slicks and enhance **natural** biodegradation where other forms of recovery or removal are not possible. Lee at al. (2011) reported on a successful field trial in the St. Lawrence River in 2008 when 55 gallons of fuel oil were mixed with chalk fines by an icebreaker propeller. The oil was naturally dispersed into the water column and did not resurface. A control test with no fines added, produced significant resurfacing. Application of this technique would be considered only as a "last resort," such as when oil was threatening a sensitive area and where no other options for removal or recovery remained. Use would require approval at a number of levels within the Unified Command with input from the NOAA Scientific Support Coordinator and Environmental Unit.

Ice concentrations are often highly variable over short distances in the same general area. Consequently, responders may need to use several response options appropriate for a wide range of ice conditions, including very open to very close pack/drift ice as well as nearshore ice environments that include stable solid fast ice (attached to land) or a continuous ice sheet in harbors.

Tracking and detection integrates data from trajectory models, ice beacon positions, and remote sensing platforms (airborne, subsea and space) to direct response resources where they are most effective; for example, working in the most concentrated and thickest oil.

The availability and flow of information from many different sources enable the spill management team to make the best decisions possible. The response team coordinates the acquisition and assessment and dissemination of spill information while typically asking questions such as:

- 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 through weathering and spreading?
- What are the resources at risk in the spill path; what are their sensitivity and vulnerability?
- What are the most feasible and environmentally acceptable response options under the conditions prevailing at the time? Net Environmental Benefit Analysis (NEBA) and its more recent counterpart, Spill Impact Mitigation Analysis (SIMA), provides a systematic framework for organizing many of these factors and assessing the relative merits of a particular response strategy in a particular situation. The Environmental Unit in the Planning Section would assist in this evaluation and selection of the best response options. This type of analysis is beyond the scope of this guide.

In an environment with stable ice and snow conditions (e.g., fast ice nearshore), the response timeline can extend for several months if the oil is naturally contained, concentrated, and trapped. In more dynamic ice conditions offshore, the decision process needs to use data on predicted (trajectory models) and monitored (tracking buoys/overflights) oil in ice movements to estimate the probable location(s) of oil and ice over, for example, a 24- to 48-hour period.

The presence of a significant ice cover slows or in many cases stops oil from spreading and dampens wave action. As a result, oil may persist in thicker, fresher films that are more amenable to burning and skimming. Emulsification rates are slower, resulting in greatly reduced waste volumes. When oil is frozen into the surface or encapsulated within the ice sheet, it can also remain isolated from key marine resources for extended periods of time – weeks or months. The presence of ice can buy time, allowing responders to wait for better conditions (e.g., a spring response to recover oil trapped in ice after the shore ice breaks up). Actively monitoring the oil until conditions improve to allow recovery/removal is a viable response strategy (Section 6.7)

Compared to a spill in open water, oil in high ice concentrations does not spread to any great extent or move very quickly as long as the ice remains concentrated (>6/10). However, Great Lakes ice conditions are highly variable over a matter of days or even hours: oil that is securely contained or trapped among ice in high concentrations may spread rapidly to create a much larger contaminated area if the ice cover opens in response to wind or currents.

In summary, while the following sections necessarily discuss individual tactics and strategies, the operational reality is that no one response option or supporting activity should be viewed in isolation. Responders may deploy multiple options in close proximity depending on local conditions. Modelling oil fate and behavior while tracking and monitoring oil and ice as they drift forms an integrated picture that informs the command center in a near real-time data stream.

Sections 6.2 through 6.5 cover individual tactics such as Ice Management and Oil Containment along with options for recovery/removal both mechanically and through in situ burning.

6.2 Ice Management

Effectively managing ice to mitigate its impact on response effectiveness is a critical component of oil spill response in ice-covered environments. Ice management is normally conducted to accomplish one of these objectives:

- Create and maintain a clear opening in the ice to expose oil for mechanical recovery or burning;
- Maintaining mechanical systems under freezing conditions (e.g., skimmers, pumps, hoses); and
- Ice booms to divert ice away from response operations.

6.2.1 Creating and Maintaining Openings in the Ice

Air Bubblers and Jet De-icers: Ice on a water body can be removed or its formation prevented by utilizing two mechanisms: surface water movement and the circulation of warmer water from lower depths to the surface. During winter, lake waters can undergo stratification, where the densest water sinks to the bottom and remains slightly warmer than the surface water exposed to freezing temperatures. Two different systems can be used to take advantage of this natural phenomenon (Figures 6-1 and 6-2):

- Air Bubblers: An air bubbler system consists of an air compressor connected to a weighted, perforated airline or pipe placed on the lakebed. As bubbles rise, they draw warmer water from the bottom to the surface.
- Velocity Jet De-Icers: Velocity jet de-icers with a power source operate on a similar principle, using a propeller to circulate warmer water upward.

Both systems also promote surface water movement, which aids in melting ice and preventing new ice formation.

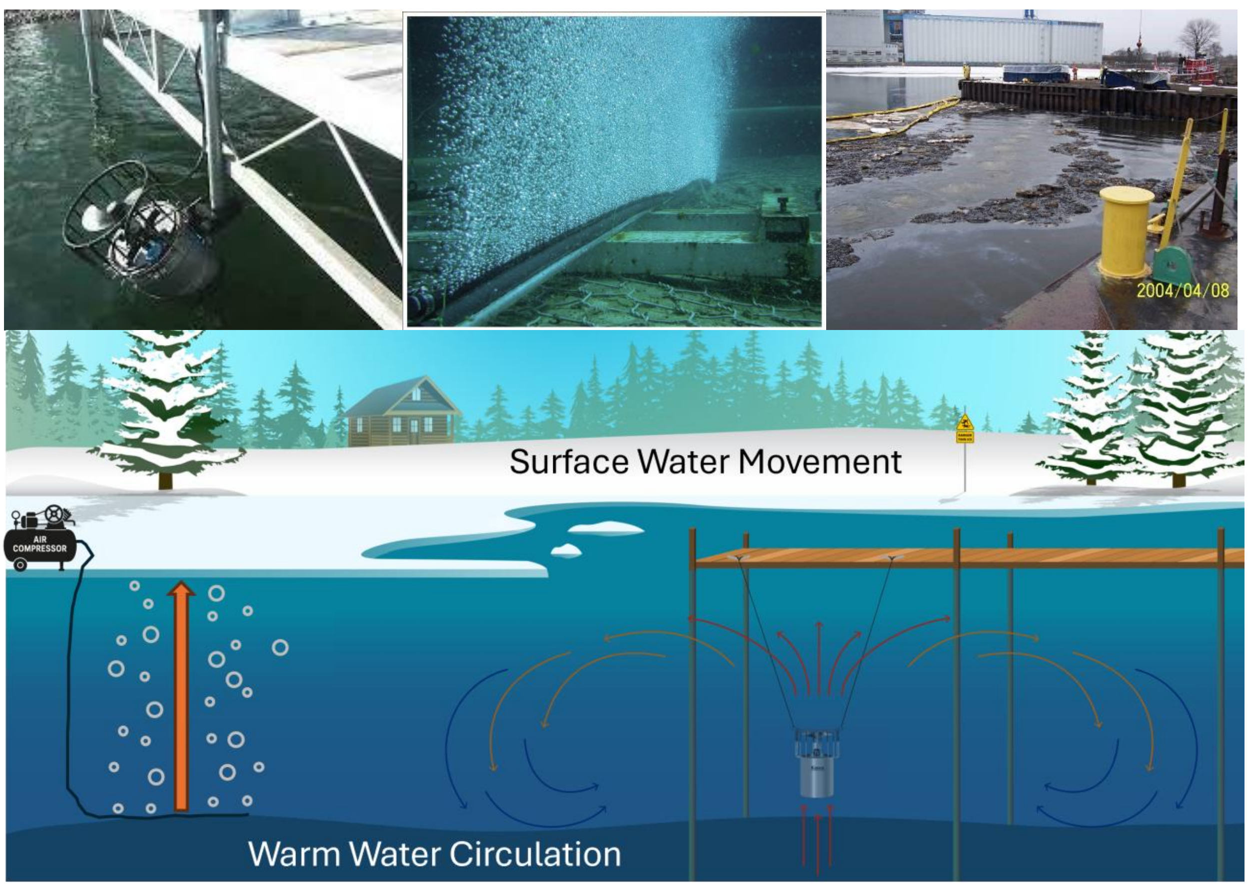


Figure 6-1. Water circulation from air bubbler systems and velocity jet de-icer. Credit: ACS.

Figure 6-2. Time lapse of velocity jet de-icer deployed in a 5 ft x 6 ft sump cut into a freshwater pond. Times are T=0 (deployment), T+1 hour, T+14 hours (approximately 16 ft diameter hole). Photos: ACS.

Once melting operations begin, workers should exercise extreme caution on or around the ice, as subsurface degradation can compromise ice strength and thickness. Safety considerations include:

- Jet Orientation: Angled velocity jets create an oblong opening in the ice, while vertical mounting results in a circular hole. Floats can be attached for horizontal mounting if surface movement is the only desired effect.
- Temperature and Depth Restrictions: A temperature difference of approximately 1° is required between the top and bottom to create the circulation needed to melt the ice. Velocity jets may be restricted to depths of less than 30 ft due to their use of mineral oil and susceptibility to implosion.
- Air Bubbler Systems: A notable benefit of air bubbler systems is their ability to function as containment or exclusion pneumatic booms with sufficient airflow (see Section 6.3).

Heavy Equipment: Heavy equipment (including skidsteers and walk-behind tracked vehicles) can be used either to remove ice from an area or modify it for other purposes, enabling access to areas needed for response operations. Additionally, creating packed paths or accumulating snow on ice surfaces can help extend the usability of these areas for ongoing response activities. However, due to dynamic, unpredictable ice conditions away from shore, the use of heavy equipment in Great Lakes response may be limited to nearshore areas where fast ice is grounded or conditions where the equipment can be operated from a vessel/barge platform. Thicker ice, capable of supporting heavy equipment, is unlikely to form reliably through most of Great Lakes Region. See discussion of ice conditions and bearing capacity in Section 2.

Breaking Ice: Ice that is too large to remove can be broken into smaller, more manageable pieces using specialized equipment. The required equipment and feasibility of this method will depend on ice thickness. One effective approach is using a wrecking ball or heavy weight, which is lifted by a crane or similar equipment and dropped onto the ice from above to fracture it (Figure 6-3). Once broken, the ice can be removed using various methods, such as a clamshell bucket, as described in Section 6.4.

Figure 6-3. Heavy steel weight breaking oiled ice in Thunder Bay. Photo: ECRC.

6.2.2 Maintaining Mechanical Systems

At temperatures below freezing, most mechanical recovery systems face operational challenges. Ice can form in pumps and hoses, motors can be difficult to start, hydraulic fluids become more viscous, and oleophilic surfaces (e.g., belts, brushes, and rope mops) may accumulate ice, reducing their oil recovery efficiency. Additionally, material failure can occur under extreme cold conditions.

Surface water exposed during recovery and containment operations (e.g., in trenches or sumps) is prone to refreezing, hindering the deployment and effectiveness of mechanical recovery systems. To address these challenges, targeted heating methods such as steam systems, hot water at high pressure, heating elements, and heated enclosures can be used.

Steam Systems: Mechanical recovery systems typically operate in or around the oil-water separation layer, exposing them to both oil and water during recovery operations. In cold weather, this water can freeze, creating ice buildup on skimming systems, skimmer sumps, oleophilic surfaces, and other tactical assets. Steam is an effective method for managing ice buildup, increasing recovery efficiency by reducing downtime and enabling skimmers to function in lower temperatures.

While other heating options are available, steam offers a significant advantage due to its continuous heat transfer through condensation. As steam condenses on a surface, its latent heat is transferred to the material, and the resulting condensate remains at the same temperature as the steam, maintaining consistent heating. In contrast, other systems experience heat loss as the source cools, leading to uneven heating and higher energy demands. Steam heating is also highly efficient, releasing 2 to 5 times more heat than the heat provided by fluids such as hot water.

The method of applying steam is as critical as the source itself. When applied to a skimmer, steam can be used either to heat the entire skimmer body or to directly target the oleophilic surface. Applying steam to the skimmer body helps prevent ice formation and melt existing ice (Figure 6-4). However, as temperatures drop and operation durations increase, icing caused by the water generated from steam can accumulate, sometimes rendering the skimmer inoperable.

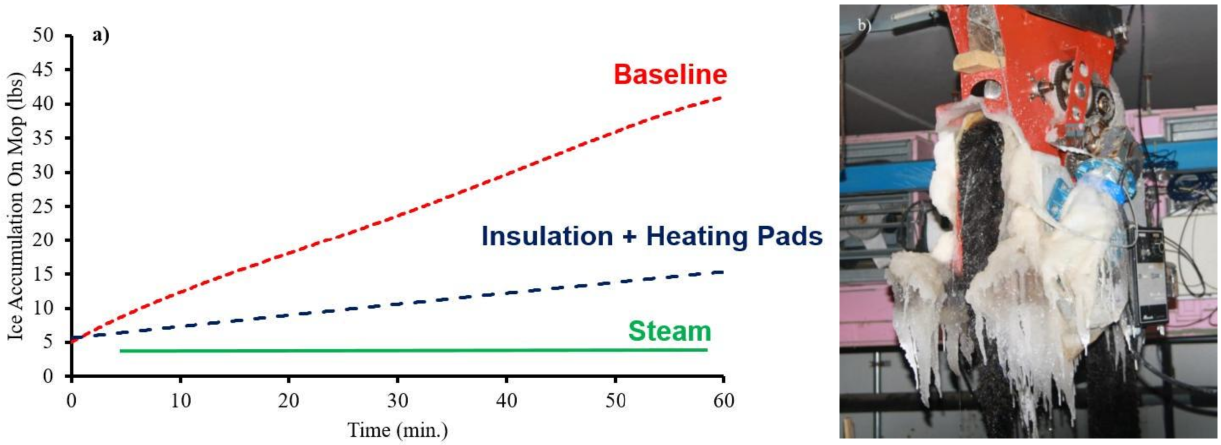


Figure 6-4. (Left) Ice accumulation on a skimmer adhesion belt at -28 C for the baseline (no heat), with insulation and heat pads, and with steam heating methods (Lamie et al. 2020). (Right) Ice buildup on an Arctic Foxtail skimmer at -28°C for 1 hour. Photo: H. Henriksen AS, Norway.

Targeting the oleophilic surface with steam has proven effective for removing ice and preventing further accumulation (Figures 6-5 to 6-7). To avoid prematurely removing recovered oil, steam should only be applied to oleophilic surfaces after the oil has been removed (e.g., by scrapers or rollers) and before it enters the water.

Figure 6-5. (Right) Application of steam to oleophilic surface. (Left) view of adhesion belt. Photos: ACS.

Steam generators are commercially available and typically manufactured for industrial cleaning. “Dry Steam” generators (superheated, saturated steam) have been found to be more effective in this application than wet (unsaturated) steam and generate less residual water.

Figure 6-6. Application of steam to skimmer body. Lamor brush skimmer with steam lines. Photo: ACS.

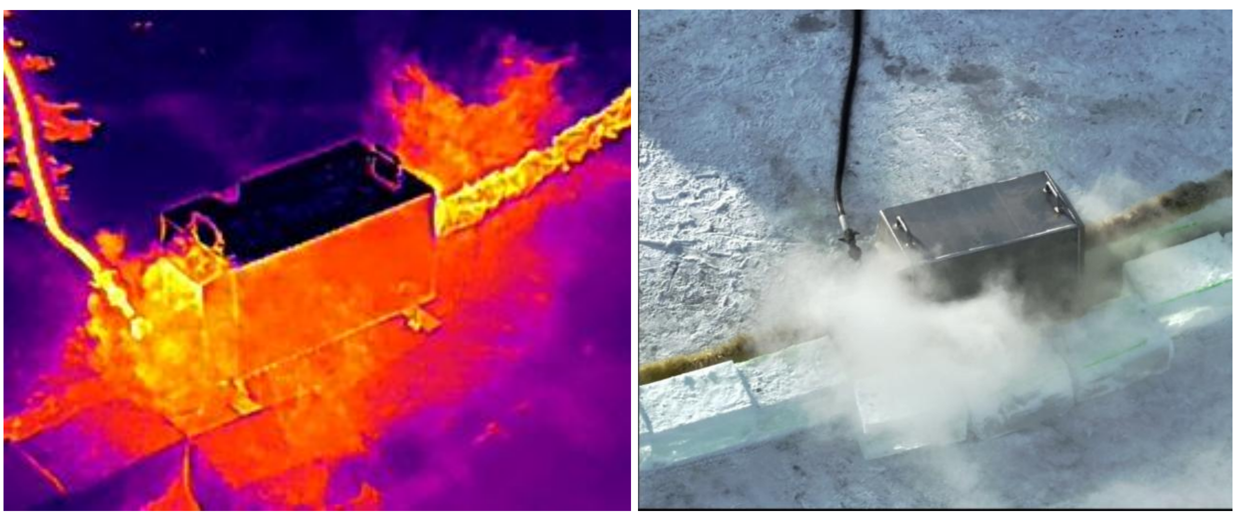


Figure 6-7. A fabricated steam collar is installed on a horizontal rope mop skimmer. The belt enters on the left, after the oil has been removed, and exits heated on the right, just before entering the recovery trench. Photos: ACS.

<u>Hot-Water Pressure Systems</u>: The use of hot-water pressure systems has been tested and, while they can effectively manage ice, they generate significant amounts of water at the target area and consume far more water compared to steam systems. Steam generators, particularly dry steam models, are more efficient, producing and consuming the least amount of water while delivering effective results.

<u>Shelters</u>: Heaters, along with portable shelters or small coverings, can be utilized around recovery locations to enhance efficiency, minimize equipment issues, and improve oil pumping (Figures 6-8 to 6-10). These shelters can be commercial varieties as described in Section 4.3 or can be made with available materials such as the one shown in Figure 6-8. Some of the heat sources described in Section

4.3 may also be applicable here to aid in recovery. A side effect of heating an enclosed space with oils present is the release and entrapment of volatile hydrocarbon compounds, which pose respiratory and flammability hazards. For this reason, heated shelters of this type should be equipped with continuous atmospheric monitoring, and heat sources should not involve open flames.

Figure 6-8. (Left) Example of small, heated shelter erected over a recovery hole to keep personnel and equipment warm. Photo: ACS. (Right) Reinforced plastic sheeting built around scaffold and held with spring clamps. Photo: Enbridge.

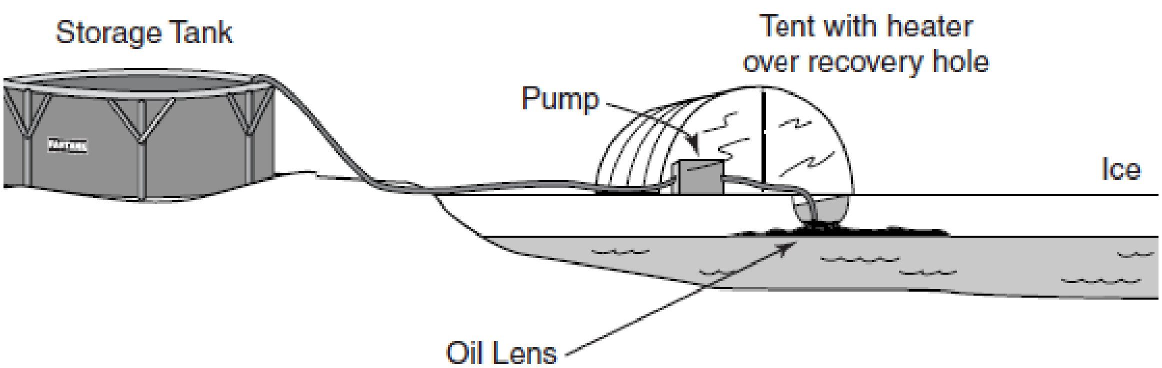


Figure 6-9. Recovered oil is pumped into storage tanks or drums outside of the shelter for safety. Credit: ACS.

Figure 6-10. Insulating openings. (Left) Blueboard foam placed over opening and covered in snow outdoors. (Right) Blueboard foam covers opening in a shelter. Photos: ACS.

Heating Hose: Common hoses used in a response include hydraulic hoses, suction and discharge hoses for recovery, and water hoses for flushing. In cold temperatures, flow through these hoses can slow or stop due to freezing or increased fluid viscosity, with hoses being particularly susceptible to freezing when flow ceases. Hydraulic hoses can function well below 0°F, but as temperatures approach -35°F, hydraulic fluid thickens significantly, increasing pressure and leading to system failure or hose rupture.

Several methods can help prevent freezing and maintain flow:

- Maintain Continuous Flow: In flushing hoses, slightly cracking the nozzle can help prevent freezing. Ensure the released water does not compromise ice stability in unintended areas.
- Evacuate the Line: When flow is stopped, walking out the hose to remove residual fluid can help prevent freezing inside the line. Lay-flat hoses may still retain residual water between their walls even after draining, which can freeze and cause the walls to stick together. To mitigate this, keeping hoses heated or having spare hoses available may be necessary if they are drained in freezing conditions.
- Apply Heat:
  - Bundling hoses together, ideally pairing them with a hose carrying heated fluid.
  - Insulated hose wraps will help retain heat.
  - Running liquid hoses inside heater trunk hoses is effective for short distances.
  - Heating the initial flow point to allow heat transfer through the line. Additional periodic heating may be required along the hose, depending on ambient temperatures and the fluid being pumped.

Heating Methods include:

- Electric heating pads
- Heaters
- Steam lines
- Hot water circulation

Hoses transporting fluids, especially warm fluids over ice, can melt into the surface, degrading the ice's weight-bearing capacity and creating uneven walking surfaces, increasing the risk of slips and falls. Elevating hoses can help minimize these impacts.

Safety Issues with steam and hot water heating systems include:

- Burns
- Ice surface degradation
- Trapped toxic vapors
- Pressure
- Reduced visibility

6.2.3 Ice Booms

Management of ice with booms has been successfully used in the past, typically involving large, heavy-duty steel booms and cables, for example protecting water intake at powerplants in the Great Lakes (Figure 6-11). Ice booms can assist in diverting ice, which may be useful in certain spill scenarios, such as conducting recovery operations up current from a subsea pipeline break (Figure 6-11). Traditional booms are also capable of collecting and diverting small amounts of ice; however, they may fail if the forces from the ice exceed their buoyancy, the strength of the boom material, or the capacity of the tension cables and connectors. Failure could be caused by the boom separating, becoming submerged, or being pulled on top and over the ice.

Figure 6-11. (Left) Diversionary ice boom up current of subsea pipeline break. (Right) Lake Erie-Niagara ice boom consists of a 1.7-mile span of floating steel pontoons linked together by steel cables and anchored to the river bottom (https://www.opg.com/news-and-media/our-stories/story/ice-booms-keep-rivers-flowing/).

6.3 Oil Containment

Oil generally needs to be contained and concentrated to facilitate recovery by mechanical means (e.g., skimmers, ice and snow removal, vacuum) discussed in Section 6.4, or removal by in situ burning (using natural ice containment or fire booms) discussed in Section 6.5.

Containing oil in the presence of ice can involve several different options discussed below:

- Trenches and Slots, including the insertion of barriers
- Traditional Containment Booms
- Natural Ice Containment
- Berms on Ice, including snow and ice and inter-tidal booms

6.3.1 Trenches and Slots

Partial trenches or through-ice slots can be cut into the ice surface to direct surface or under-ice oil flow toward a collection point (Figure 6-12). Trenches are not cut all the way through the ice, while slots extend through the entire ice thickness to the water below. Both methods involve cutting an opening in the ice at a set distance and width, followed by crosscuts to create removable ice blocks. The size of these blocks depends on containment needs and the capability to lift and remove them.

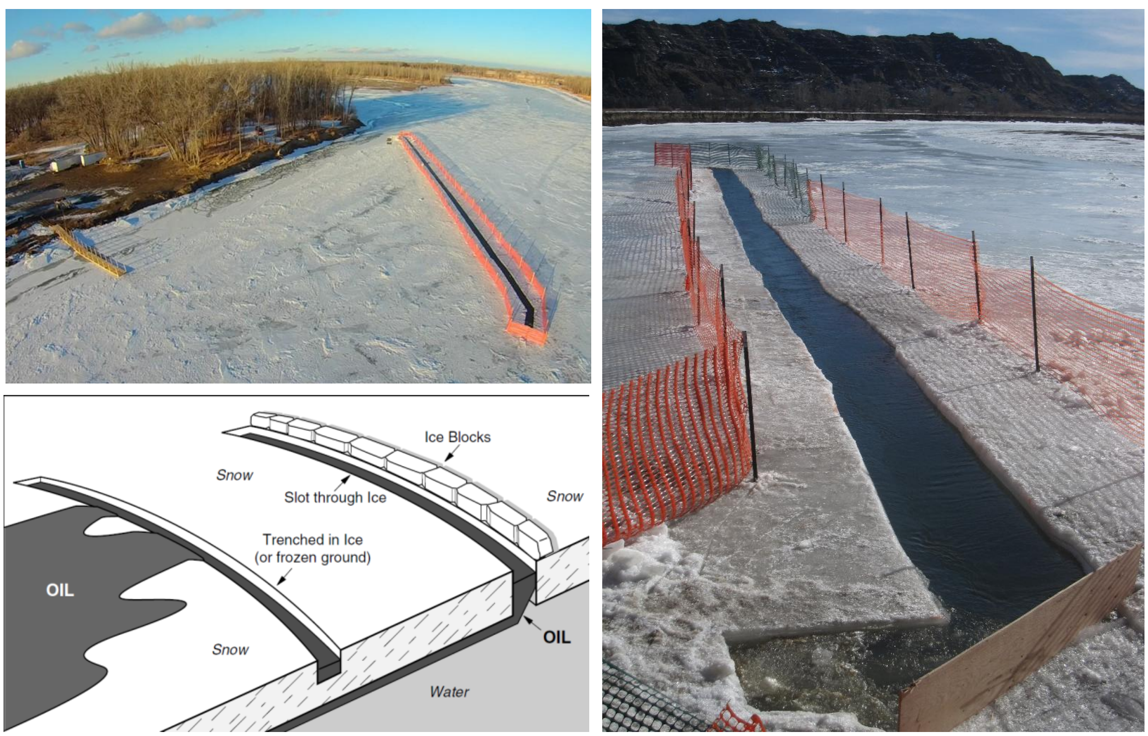


Figure 6-12. Clockwise from top left. 320 ft ice slot on the Yellowstone River. Photo: Enbridge. Close up of ice slot to recovery area from Bridger Pipe release, Glendive, MT. Photo: EPA. Side view of surface trench, and slot (Alaska Clean Seas 2015).

Trenches are primarily used to contain oil traveling on the surface and to create a collection point for recovery. They can be reinforced using ice block walls, boom with its skirt laid across the bottom of the trench and flotation above, or snow berms, all of which enhance containment effectiveness.

Trenches can also be used to collect oil trapped under ice in areas with oil pockets. In this method, a trench is cut, and an auger hole is drilled through the bottom. Floating oil pushes up through the hole, filling the trench and any connected sump (Figure 6-13). This approach helps minimize oil spread across the ice surface, which can occur when cutting slots directly through an oil pocket.

Figure 6-13. Trench and recovery sump cut into ice over an oil pocket. An auger hole is drilled through the ice within the trench or sump, allowing oil to rise through the hole and fill the recovery area. Photo: ACS.

Heavy equipment can be used to excavate trenches along shorelines in ice and soil, making it an effective method for containing oil spills that originate on land and flow toward the water or for capturing oil that has washed up into the shoreline and ice. A trench is dug with an excavator along the length of the impacted area, allowing oil continuing to flow toward the water to be contained before reaching the shoreline (Figure 6-14). Additionally, mobile oil entrapped among ice rubble can migrate into the trench, where it can be more effectively recovered.

Figure 6-14. Trenching on shoreline with excavator. Photos: Enbridge.

Slots are used to capture oil beneath the ice. They can be cut directly across pockets of trapped oil or, in moving water, angled to the current to act like a boom. As oil surfaces inside the slot, it is directed along the slot's length to a collection area, often leading to a sump large enough for the recovery system in use. Slots are useful placed down current from the oil release.

6.3.2 Barriers Under Ice

Sheets made out of plywood, plastic, or metal, or boom skirts can be inserted through slots cut in the ice using frame-mounted saws or trenchers to contain or deflect oil beneath the ice. The cutting process follows the same method described in “Cutting”, except that instead of removing ice blocks, the slot created by the saw or trencher, which is the same width as the cutting tool, is used to insert the barrier (Figure 6-15, Left).

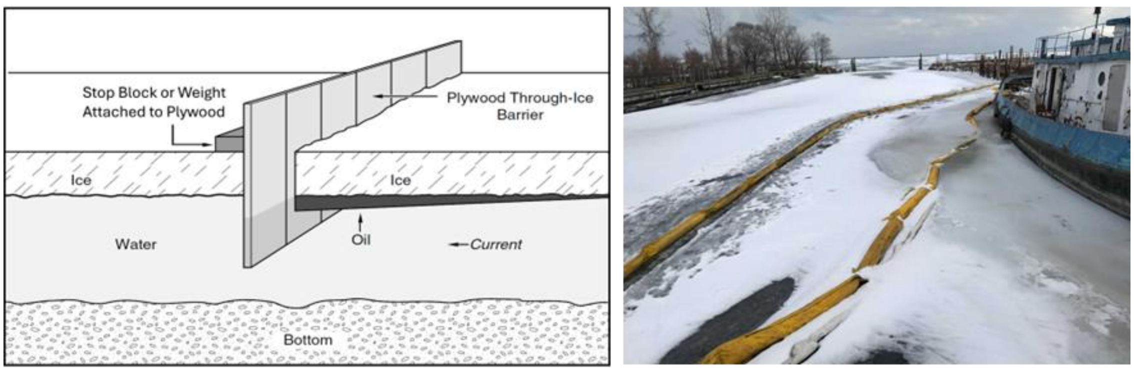


Figure 6-15. (Left) Plywood barrier concept viewed from the side (ACS 2015). (Right) Boom placed in slots cut through ice. Photo: Enbridge.

To ensure a proper fit, plywood thickness must be narrower than the saw or trencher width. If the slot is too tight, the boards may freeze in place or become stuck. Additionally, because plywood is buoyant, it must be weighed down or secured to the ice surface to prevent it from being pushed up and losing effectiveness. This can be done using fasteners, brackets, or weights like sandbags.

Boom can also be used in slots similarly to plywood barriers. Slots wide enough for the boom and skirt to pass through are cut in the ice using a chainsaw sled. The boom is then placed in the slot with the skirt extending below the bottom surface of the ice (Figure 6-15, Right). This method can be used to either contain oil within an area or divert it to a recovery site.

Cutting long sections of ice to insert either plywood or booms can be very labor-intensive if a trencher is unavailable. If this is a concern, barriers can be placed strategically in locations where oil is expected to collect and thicken.

6.3.3 Ice Cutting

The choice of cutting equipment depends on logistical access, ice thickness, and the ice’s weight-bearing capacity:

- Trenchers – In fast ice or sufficiently thick ice, equipment-mounted trenchers are highly effective (Figure 6-16). Though heavy, they are ideal for cutting long trenches quickly.
- Chainsaws – In thinner ice or for shorter spans, chainsaws are a versatile cutting tool. They can be used either for free-cutting or with a chainsaw sled.

Figure 6-16. 72” trencher attached to skid steer loader. Photo: ACS.

Chainsaw sleds hold chainsaws in a fixed position at a desired cutting depth, ensuring precision and efficiency (Figure 6-17, Left). They vary in design, with some configured to hold the saw vertically and others horizontally, but all typically operate on runners and are pulled along the ice to create a trench or slot. Common features include:

- Protective barrier around the chainsaw bar for safety;
- Visibility or reference points to help maintain a straight cutting path; and
- Adjustable saw depth settings for consistent, repeatable cuts.

Chainsaws offer another key advantage in that they can reliably cut a vertical, near-90-degree edge. The angle of the cut plays a crucial role in ice block removal. Angling the saw away from the center of the slot or trench can create blocks that are difficult to extract. In contrast, angling the saw inward toward the center helps form blocks that are more easily removable. Some chainsaw sleds are specifically designed to cut at this angle for improved efficiency (Figure 6-17, Right).

Figure 6-17. (Left) A horizontal chainsaw sled designed to cut blocks at an angle, creating a wedge shape for easier removal. (Right) An ice block being pulled from a slot after cutting. Photos: Enbridge.

Free-cutting with a chainsaw is an option, especially as ice thickness decreases. However, maintaining a straight cut and consistent angle is more difficult without a sled. While chainsaw bars exceeding 72 inches are available, their length makes them unwieldy to use, and the bar tends to curve over its length, resulting in curved walls that make ice block removal more challenging. Additionally, free-cutting with a chainsaw often requires personnel to work in bent-over or kneeling positions (Figure 6-18). These poor ergonomic postures can lead to fatigue and limit the duration personnel can cut effectively.

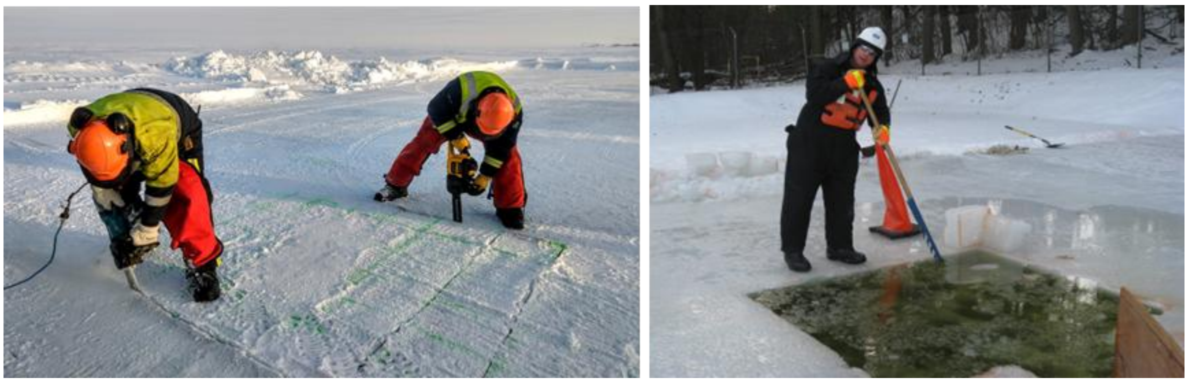


Figure 6-18. (Left) Free cutting with electric and battery powered chainsaws. Note the need to bend at waist resulting in poor ergonomics. (Right) Long, thin ice-fishing saws are also a good choice for smaller blocks and crosscuts in trenches. Photos: ACS.

The ability to produce repeatable cuts at a consistent depth is particularly useful when removing ice blocks for trenches. When removing ice blocks from trenches, a common practice is to strike the base of each block with a heavy bar. If all the ice blocks are cut to the same depth, they will shear cleanly along their bases. If the depths of the cuts vary, the ice may fracture and remain attached at the bottom, making removal more difficult (Figure 6-19, Top Right).

Setting up for cutting is more efficient when the outline of the cuts is marked on the ice beforehand. This can be easily done using a length of rope and spray paint. Holding the rope between two points creates a straight reference line, which can then be sprayed over to establish a clear cutting path (Figure 6-19). When cutting slots, slightly widening one end can make block removal easier. Once the crosscuts are complete and the first block is removed, the next block can be shifted into the widened space, allowing for easier insertion of ice lifting tools. In areas with current and sufficient depth, blocks can also be pushed underneath the ice, eliminating the need for lifting and reducing tripping hazards.

When cutting slots, water and/or oil will be drawn up by the saw and can spray above the ice surface. Many chainsaw sleds help redirect this spray to the ice surface, limiting its spread to the immediate area. Chemical suits and waterproof PPE are recommended when cutting slots free handed.

Water from slotting can coat and freeze equipment, particularly the saw bar and chain. If the saw stops moving in cold conditions, ice can quickly form, seizing the bar and chain. To prevent this, it is good practice not to stop the saw while the bar is still in the ice. Additionally, be prepared to thaw the bar and chain as outlined in Section 4.3.

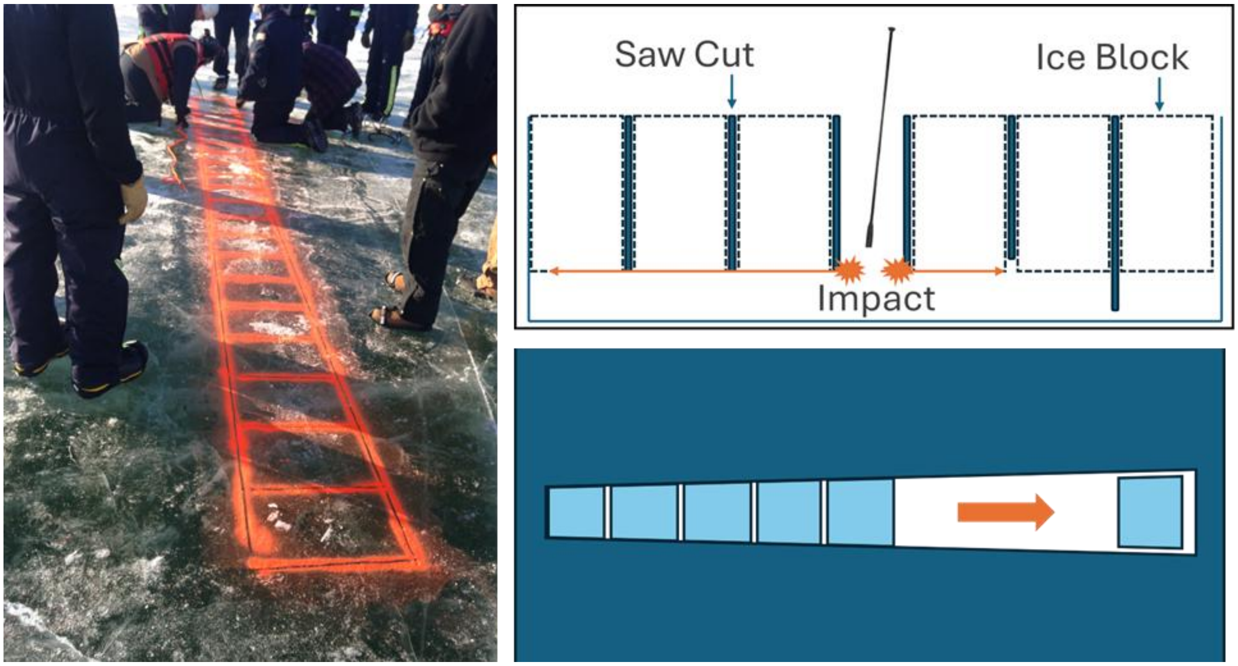


Figure 6-19. (Left) Using a rope and spray paint to mark cutting lines on the ice. Photo: ACS. (Top Right) Cutting ice to a consistent depth allows blocks in a trench to be easily and cleanly broken out along a shear line, while varying cut depths can prevent clean breaks. (Bottom Right) Widening one end of the slot makes it easier to slide and remove blocks cleanly. Credit: ACS.

Use a combination of ice lifting devices to manage lifting out ice blocks (Figures 6-20 and 6-21). Chainsaw operators must ensure the blocks are not too large for one or two people to safely lift and carry out of the way. See Table 6-1 for the weight of ice of different thickness and area. Ice screws used for ice climbing are ideal to use as anchors and for removing small blocks. T-bars and tongs may be shop fabricated in different sizes and configurations. Larger blocks may require A-frames or heavy equipment.

Figure 6-20. (Left) Examples of ice screws, T-bar, split-pin (or chain-linked) Lewis lifting devices, and an ice fishing handsaw. (Right) Smaller blocks may be removed using T-bars. Photos: ACS.

Figure 6-21. One- and two-person ice tongs are used to lift small- and medium-sized blocks from the trench. Photos: ACS.

Table 6-1. Weight of ice in pounds per cubic foot.

Ice Thickness *(In Inches)*	Surface Area *(In Square Feet)*																
	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	40	50
6	57	114	172	229	286	343	400	458	515	572	629	686	744	801	858	1144	1430
12	114	229	343	458	572	686	801	915	1030	1144	1258	1373	1487	1602	1716	2288	2860
18	172	343	515	686	858	1030	1201	1373	1544	1716	1888	2059	2231	2402	2574	3432	4290
24	229	458	686	915	1144	1373	1602	1830	2059	2288	2517	2746	2974	3203	3432	4576	5720
30	286	572	858	1144	1430	1716	2002	2288	2574	2860	3146	3432	3718	4004	4290	5720	7150

Note: The colors are a gradient relative to "0", to convey visually that weight is increased as the total volume increases, with green being the least and red being the most.

6.3.4 Traditional Containment Booms

Containment in ice with traditional booms and skimmers presents significant challenges. Relatively small amounts of drift ice (as little as 10% coverage) or slush/brash between the larger floes can interfere with the flow of oil to the skimmers and result in realistic recovery rates being far less than a skimmer's theoretical capacity (Bronson et al. 2002; Potter et al. 2012; Schmidt et al. 2014). The presence of very open drift ice (1-3/10) can interfere greatly with boom towing and require frequent maneuvering to avoid the boom collecting too much ice and possibly failing.

Dealing with a large spill may involve miles of containment boom managed by many vessels to concentrate these thin oil slicks enough to enable effective skimming. The *rate* at which a single skimming system encounters the slick moving at typically less than ~0.8 knot forward speed (to avoid boom failure and oil loss) is the key limiting factor controlling the total volume of oil that can be practically recovered as a percentage of the oil spilled. In ice concentrations less than 6/10), most crude oils and products like diesel and gasoline spread rapidly to form a very thin layer on the water surface (much less than one 0.04 inches or 1 millimeter).

When towing boom with or without the presence of ice, it is critical to use a vessel that can maintain a continuous speed of 1 knot or less (~0.8 knot preferred). Many vessels lack the ability to operate at such low speeds for prolonged periods without damaging their gearing. Controllable pitch propellers are essential. Tugboats, readily available in some areas of the Great Lakes, have successfully towed boom in broken ice at speeds below one knot in tests in Alaska.

Boom vanes: Boom vanes allow a single vessel to conduct booming operations that would typically require two vessels (https://www.elastec.com/products/floating-boom-barriers/accessories/boomvane/). A boom vane can be used to tow a J-boom configuration or deploy a Current Buster system. A key feature of the boom vane is its recovery mechanism, which allows it to be retrieved by pulling on a line, bringing the vane back to the deployment vessel. This can be used to maneuver around large ice floes when operating in open water or light ice concentrations. Boom vanes require a minimum water flow or vessel speed of 1 knot to function properly**.** As with any booming operation in the presence of ice, the practical deployment of boom vanes will generally be limited to very open drift ice.

Natural ice containment**:** As ice concentrations exceed the operating limits of conventional containment booms (~3/10 ice concentration), natural containment provided by the ice begins to maintain the oil in thicker films, thereby limiting the overall contaminated area. As the ice coverage exceeds ~6/10, the oil becomes largely contained by the ice without the need for booms. There is an intermediate zone of ice concentration where there is too much ice to successfully deploy and tow containment boom and too little ice to ensure effective natural containment. This transition region or “grey” zone with no practical means of containment occurs with ice concentrations between ~3/10 and 5/10. The actual threshold concentrations can vary up or down depending on the distribution of the ice (i.e., the predominant floe size). For example, it may be possible to tow booms through a 4/10 concentration ice field if the floes are medium size or greater (300 ft and up). See Section 2.2 and Appendix A for additional information on ice types and terminology.

Ice edges such as fast ice or big floes can be used to aid in oil containment and collection. Ice edges have been used to act as a barrier to herding oil with streams or jet of water. Boom can also be positioned to help contain oil against the ice edge for subsequent mechanical recovery or in situ burning. Winds will naturally move the oil to collect in thick enough films for burning against an ice edge (Section 6.4.8).

6.3.5 Berms on Ice

Snow and Ice Berms: An ice berm can be constructed around heavily oiled areas to contain oil or diesel spilled on ice. Typically, these berms are made from ice blocks removed during trenching or slotting. They can be reinforced by packing snow around them and spraying the snow under freezing temperatures to improve containment (Figure 6-22). A related containment method involves creating snow berms on the ice surface to prevent oil from spreading. These can be built using hand tools, ATV-mounted plows, small walk-behind skid steers, or larger heavy equipment, depending on the urgency and scale of containment needed (Figure 6-23).

Figure 6-22. (Left) Ice berm built around a recovery sump with plywood barriers funneling oil under ice into the sump. Photo: ACS. (Right) Ice blocks being removed from a slot and placed along the edge to create a berm. Photo: Enbridge.

Figure 6-23. (Left) Walk-behind skid steer creating a snow berm. (Right) ATVs with plows create snow berms. Photos: ACS.

For rapid containment, snow can simply be stacked to form the berm. If a stronger barrier is required, the snow berm can be sprayed with water to ice it in place. The berm can be built in layers from the base up, with each layer sprayed and frozen before adding the next, ensuring that the berm freezes solid throughout, rather than just on the surface, increasing its durability.

<u>Intertidal Boom on Ice:</u> Inter-tidal boom consists of three chambers arranged in a pyramid shape (Figure 6-24), with the bottom two chambers filled with water and the top chamber filled with air. While originally designed to rise and fall with the tides while maintaining containment, this boom can also be used as a berm on ice.

To deploy, the boom is laid out, and the bottom chambers are filled with water. Depending on the level of containment needed, a single bottom chamber may be used instead of both. Water for filling can come from any nearby or accessible source, including under the ice. Tests on the Alaskan North Slope have shown that using warm water creates the best seal once frozen. If multiple sections are used, the connectors may need to be reinforced with plastic and/or snow to prevent oil from leaking past. A smaller single-chamber version has been developed by Alaska Clean Seas. Once frozen, the boom will not be recoverable until it thaws.

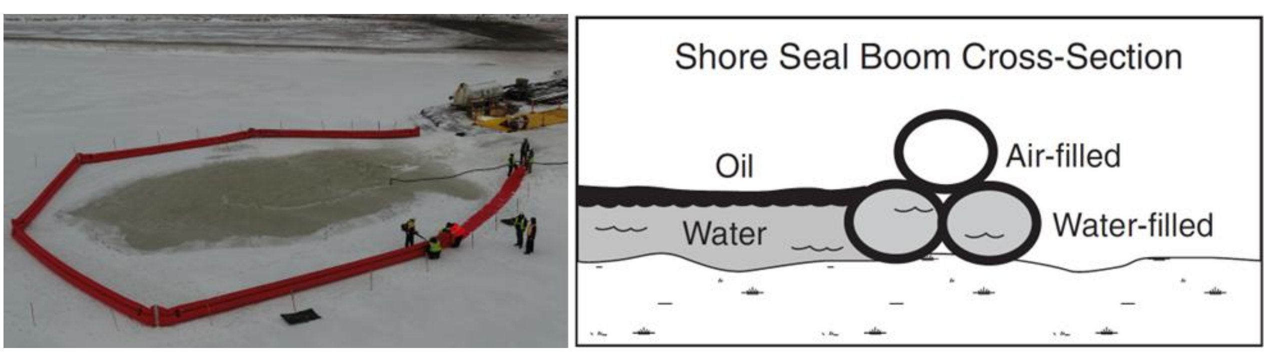


Figure 6-24. Intertidal shore seal boom on ice (left) and diagram of the chambers. Credit: ACS.

6.4 Recovery or Removal

After managing the ice and/or containing the oil (naturally within the ice or within booms) the next steps involve recovering the oil mechanically or removing it from the marine environment through burning. The following subsections discuss the applications of several mechanical recovery tactics:

- Skimming
- Direct Suction
- Sorbents
- Oiled Ice/Snow Direct Recovery
- Viscous Oil Pumping
- In Situ Burning

Having the ability to support heavy loads safely on thick, stable ice is key to implementing many of the on-ice tactics commonly used in areas such as the North Slope of Alaska (2.5). In the Great Lakes, the situation is very different. With few exceptions, such as rivers or protected water bodies, the ice cover in the Great Lakes lacks the ice thickness, stability and predictability to support the use of heavy equipment such as loaders, or dump trucks any significant distance from shore.

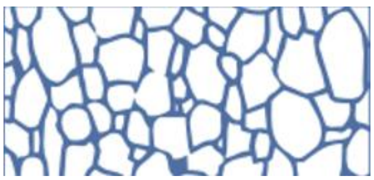
It may be possible to utilize snow machines and sleds, airboats or small hovercraft to transport personnel and light equipment close to shore or in more confined bays and rivers, but not to safely venture into deeper water with moving ice. In most cases, offshore response with heavy mechanical systems will require vessel/barge support.

Where continuous stable ice exists around the spill site to potentially support response teams, it will be necessary to estimate the safe bearing capacity before putting equipment or personnel or lightweight equipment on the ice. This is done by profiling the ice for thickness and taking samples to determine the internal condition of the ice sheet (Section 2.5).

Ice concentration plays a key part in determining which skimming or burning tactics are practical and effective in a mobile ice cover offshore (Table 6-2). For nearshore spills, additional tactics become possible with a greater likelihood of having a thicker, more stable ice cover that safely supports on-ice operations, using for example: sorbents, direct oil pumping, and direct recovery/removal of oiled snow and ice.

Table 6-2. Considerations for practical and effective skimming or burning tactics for different ice concentrations.

Ice Concentration	Skimming or Burning Tactic Considerations
0 to 3 tenths - Very open drift ice 	• Oil spreading and movement not significantly affected by ice. • Conventional open-water mechanical recovery techniques using towed boom and skimmers and fire booms can achieve some success. However, as the ice concentration increases, so does the frequency and severity of ice interference; as a result, the overall recovery rate starts to fall with ice concentrations as low as 1-2/10 and drops substantially with concentrations over 3/10.

Ice Concentration	Skimming or Burning Tactic Considerations
4 to 6 tenths - Open drift ice 	• Oil spreading slowed by ice but not fully contained. • Difficult to maneuver booms successfully. • Attempt uncontained burning of thick slicks at the upper end of the concentration range and where oil is herded by wind against an ice edge. • Vessel-towed boom sweeps can be replaced with short sections of boom connected to a skimming vessel with “side arms” to increase maneuverability, allowing the vessel to steer to avoid some of the ice (depending on floe size). Because the encounter rate is then limited by the more restricted swath width mechanical recovery is most applicable to relatively small-localized spills, or patches of oil encountered in openings between medium-sized floes or larger (≥300 ft).
7 to 9+ tenths Close to very close pack ice – Figures 1-6 and 1-5. 	• Floes touching at some point, oil effectively contained. • Recovery by skimming highly localized with reduced recovery. • Thick slicks trapped in ice are often thick enough to ignite and burn effectively • Continued mechanical recovery in these conditions requires specialized skimmers mounted on ice-strengthened response vessels that are not generally available in the Great Lakes. Because of the need to frequently reposition the skimmer into fresh pools of oil, the overall recovery rates are generally quite low. • In situ burning of oil contained in thick films on the water surface or mixed with slush between floes.

6.4.1 Skimming

Skimming oil in the presence of ice presents challenges, primarily due to the difficulty of directing sufficient oil to the skimmer while also dealing with ice. Ice interferes with booms' ability to concentrate oil toward a skimmer, limits the skimmer’s direct contact with oil, and reduces the selection of skimmers that can function without damage. As ice concentrations approach 6/10 and greater, oil spreading is significantly reduced, leading to localized thickened oil pools or pockets. While this aids recovery by increasing oil thickness, it requires targeting these isolated pockets individually rather than skimming oil concentrated in large open apex booms. Mechanical recovery can work effectively in a range of ice conditions if the spill is relatively small and localized.

Specialized Arctic skimmers developed in Finland, Norway, and Denmark include improved oil and ice processing; ability to handle larger volumes of cold viscous oil and oil/ice mixtures with low water uptake; and heating of critical components to prevent freezing. Some manufacturers have modified skimmers to improve performance in icy conditions. Examples of different brush skimming systems applicable to spills in ice are the Desmi Helix, and Desmi Polar Bear. The Lamor Oil Recovery Bucket (LRB) is a modified brush skimmer mounted in an excavator bucket on an articulating hydraulic boom arm or crane (Figure 6-25, Left). This configuration helps manage ice debris, enables skimming in oil pockets, and can move ice floes out of the way using the bucket. The Framo Polaris Skimmer is a self-propelled brush skimming system (Figure 6-25, Right).

Some skimmers use ice cages in an attempt to shield skimmers from ice damage and block larger pieces of ice, while oil continues to flow through). However, these cages can be large and limited in effectiveness. In dense ice, the cage openings may clog, preventing oil from entering.

Large ice-capable skimmers require vessels with sufficient deck space and lifting capacity. More compact, lightweight skimmers may lack the mass to settle into dense ice debris or withstand ice forces.

Figure 6-25. (Left) Lamor LRB skimmer recovering oil in ice. Photo: Syke. (Right) Framo prototype self-propelled Arctic skimmer being tested in the Norwegian Barents Sea in 2009. Photo: Ivar Singsaas, SINTEF.

Regardless, careful maneuvering of the parent vessel is needed to minimize disruption to the ice cover and maintain the trapped oil pool as thick as possible.

As ice sheets become thick enough to support workers and equipment, small brush or oleophilic skimmers can be used alongside trenches, slots, and recovery sumps to contain and concentrate oil (see Section 6.3) for recovery by skimming or direct suction, whether on the surface or beneath the ice. Rope mop skimmers can be placed directly in trenches or slots (Figure 6-26), while larger skimmers require a recovery sump to function. These sumps are strategically positioned to collect oil flowing from trenches and slots. Depending on ice thickness, they can be cut entirely through the ice or partially, as outlined in Section 6.2. If the recovery sump does not extend fully through the ice, it must be deep enough to allow the skimmer to float and operate properly.

Figure 6-26. Rope Mop skimmer placed in a trench. Photo: ACS.

6.4.2 Direct Suction

Recovery with direct suction is possible in any ice concentration but is most effective where oil has is available in contained thick pockets. In unstable or thin ice conditions, recovery can be conducted from a nearby shoreline or vessel (Figure 6-27). Small drum-mounted vacuum units can be placed on a small vessels deck. On thicker ice or along shorelines, vacuum trucks and portable vacuum units can recover oil pools trapped in rough ice near the shoreline. Tracked vacuum units are available for rough terrain.

When using suction, minimizing the intake of debris is important. Screens on the suction end can help reduce debris and ice from entering the system. In cold temperatures, vacuum system components can freeze, especially when large amounts of cold air are drawn in instead of primarily fluids, exacerbating icing issues.

Figure 6-27. (Left) Recovery of oil on thin ice using vacuum systems from airboats on the Yellowstone River. Photo: Enbridge. (Right) Recovery of oil from a trench using direct suction with a peristaltic pump. Photo: ACS.

6.4.3 Sorbents

Snow can be used as a deliberate sorbent material for small spills. The resulting snow-oil mixture can be transported for melting and oil recovery onshore or possibly burned on site if the oil content is high.

Manmade sorbent booms and pads are effective at recovering small spills but create a large waste stream. This is of particular concern in remote areas where removing bags of oiled sorbents may be logistically challenging. Every effort should be made to recover/remove oil and oily waste with mechanical means (skimmers, direct suction, manual) or in situ burning before using sorbents on a large scale.

6.4.4 Oiled Ice/Snow Recovery/Removal

Oiled snow can be recovered manually using hand tools or by heavy equipment such as skid steers and loaders. Oil mixed with snow on top of rough deformed ice (ridges or rubble) may be very difficult to recover with sufficient oil content to make the operation practical. Transport of small volumes of oiled snow to shore may be possible with sleds or tracked vehicles, if the ice conditions allow. Recovered oiled snow can be transported in lined dump trucks to an approved land-based disposal site (line pit) for melting and subsequent skimming.

Oiled ice can be recovered with one of two approaches. The first is to recover the oiled ice by mechanically removing it from the water and placing it into storage prior to processing disposal (Figure 6-28). For example, crane-mounted clamshell buckets operating from shore or a barge are used to scoop up oiled ice and deposit it in tanks or dump trucks for transport to a disposal site. This can be a quick method to clean up oil contaminated ice nearshore or in a protected harbor if the crane buckets can reach the oil. However, recovery of even a few tons of oil will involve processing a lot of ice. In the 1998 *Saraband* tanker spill at Quebec City, 1,400 tons of ice were removed to collect 10 tons of bunker fuel, corresponding to 7% oil by weight. The volume of contaminated ice could be a major constraint when storage and transport of material options are limited.

Figure 6-28. Clamshell bucket being used to scoop up oiled ice (left) and deposit it into a lined container (right) for transport to disposal site. Photos: Enbridge.

Another approach is to separate and remove the oil from the ice before transport. This can be done in some cases by flushing the ice surface or by lifting ice out and rinsing it over containment tanks or a boomed area (Figure 6-29). In both cases the free oil can be recovered by skimmers or removed by burning. Cleaning ice in this manner would only be practical for small, localized spills.

Figure 6-29. (Left) Skimmer being flushed clean over oil and ice in a containment boom. This is the same procedure that could be used flush ice blocks. Photo: T&T. (Right) Flushing contaminated ice surface from small boat. Photo: D. Dickins.

For ice sheets with oil on the surface, surface flushing and washing can be an effective recovery method. Several variations of this approach can be used successfully. Oil can be washed from the ice surface into adjacent open water, directed into a trench for recovery or, in the case of viscous oil, manually collected in buckets.

Water can be sourced from various locations, including the surrounding water body or beneath the ice. Water pressure and flow should be adjusted based on conditions. While higher pressure may be beneficial on flat ice sheets, in broken ice rubble along shorelines, excessive pressure can drive oil deeper into crevices. If available, warm or hot water can help release oil from the ice.

Heavy equipment can be used to clear oiled ice and frozen beach sediments after a shoreline spill. *This approach is viable in areas with grounded fast ice or during winters where the floating ice along the shore grows thick enough to support heavy equipment.* Any decision to proceed with invasive beach cleaning will require an analysis of environmental risks and benefits.

6.4.5 Oil Transfer and Storage

Transfer pumps and storage are essential components of the recovery system. In cold and icy conditions, challenges include ensuring the engine starts reliably, preventing fuel from gelling in diesel-powered units, and draining the pump housing after use to avoid freezing. Before starting operations, frozen pumps should be fully thawed to prevent damage.

For long-distance pumping, it may be necessary to set up pumps and storage tanks in series. This involves transferring recovered material through intermediate storage tanks, allowing for staged pumping until it reaches its final destination. Proper staging of pumps and tanks helps maintain continuous flow and reduces the risk of freezing-related blockages.

Storage options for open water or light ice concentrations include barges and bladders. As ice concentrations increase, barges remain viable, but bladders become unreliable due to potential damage. Portable collapsable tanks can be placed on the support vessel, but these tanks can take up significant deck space, especially if additional tie-downs are required for securing them.

Heavy oils placed in portable storage can be difficult to offload. Storage containers with smaller valving can restrict flow. The introduction of heating to the storage can reduce viscosity and allow for the oils to flow to offloading ports and the pumps. Localized heating inside can be accomplished with hot water or steam.

6.4.6 Viscous Oil Pumping

Much of the petroleum products transported through the Great Lakes consist of heavier products such as heavy fuel oil, asphalt, tar, and pitch. These oils tend to have higher viscosities than lighter oils. Additionally, cold temperatures and the emulsification of oil can further increase viscosity during recovery operations, making it more difficult to maintain or initiate pump flow.

There are several approaches to enhance the pumping of viscous oils. One method involves applying heat to raise the oil temperature before pumping. When oil is recovered into a storage container, the entire volume can be heated using inserted heating coils. This approach can also be applied to onboard tanks of vessels. However, generating or sustaining the amount of heat required to warm the full volume of oil may not be feasible, especially in cold climates or submerged vessels. An alternative approach is to apply heat locally—either near the pump intake or around the pump body—using heating coils or steam/hot water. This method may be more practical in field conditions.

Another technique is annular water injection. This technique involves injecting water into the discharge side of the pumping system, between the pump and the discharge hose. The water forms a low-viscosity boundary layer between the oil and the inner hose walls, reducing friction and increasing both flow rate and pumping distance.

Annular water injection can also be applied to the intake side of the pump, provided a non-emulsifying pump is used. If annular water injection is applied to a pump that emulsifies oil and water, the resulting mixture can further increase viscosity and hinder performance. In these setups, steam or hot water is introduced through the annular water injection flange at the pump intake to warm the pump body, reduce oil viscosity at the intake, and lubricate internal surfaces.

Annular water injection can be used simultaneously on both the intake and discharge. While hot water is recommended for the intake side to reduce viscosity, ambient or cold water is usually sufficient for the discharge side to reduce friction.

One limitation of annular water injection is its susceptibility to freezing conditions. Since water is introduced into the system, freezing can occur. If the flow stops, restarting flow with cold water may be ineffective. Instead, hot water should be used on both the intake and discharge lines to restore operability.

Several positive displacement Archimedes screw pumps have been successfully tested with annular water injection systems, including the Desmi DOP-250, Pharos Marine GT185, and Lamor GT-A pumps.

6.4.7 Decontamination

Decontamination applies to personnel, vessels, and equipment.

Personnel decontamination can take place on ice, land, or aboard vessels. While traditional decontamination methods typically apply to oil spill response in ice-covered waters, several key considerations must be addressed.

Personnel should have access to a heated shelter for donning protective equipment and for conducting decontamination. Section 4 outlines various cold-weather shelter options suitable for this purpose. Ideally, PPE should be donned in a warm, sheltered environment. Many types of chemical protective clothing, such as gloves and chemical booties, become stiff and difficult to put on when cold. Keeping these items warm eases donning. Additionally, using oversized clothing can help. For example, oversized chemical boots can more easily fit over bulky winter boots.

In cold-weather conditions, water-based decontamination methods (e.g., rinsing or washing) are generally discouraged. Instead, disposable chemical clothing should be used and removed for disposal after use. Removal should be done by tearing or rolling the clothing off the responder, turning it inside out. This method can produce significant waste, which may be challenging to manage in confined areas such as vessels if not properly planned.

One important consideration regarding decontamination in cold-weather responses is that atmospheric testing readings are often higher *inside* the warm decontamination areas (contamination reduction zone) than outside in the exclusion zone. This is due to the colder outside temperatures reducing the release of light ends in the active work areas. However, when responders enter warm up shelters and decontamination areas, the warmer indoor temperatures can cause the release of light ends and subsequent rise in air monitoring readings. To prevent this, oiled protective outer garments should be removed, bagged in oily waste bags, and stockpiled outside in secondary containment (such as an open-top, folding, portable tank) until transferred to the waste disposal area.

Some PPE items must be worn over outermost layers to remain effective. Harnesses, PFDs, and traction devices should be worn over chemical suits and booties. These items will likely become oiled during operations. Instead of cleaning or disposing of them after each use, they can be stored in the contamination reduction or exclusion zone and reused by incoming responders.

On vessels, personnel decontamination is constrained by space. Before operations begin, clearly designate support, contamination reduction, and exclusion zones on the vessel. Support zones will typically include interior areas such as pilot houses and below-deck rooms. To prevent oil from being transferred into these areas, decontamination practices should include boot and clothing inspections, and placing white sorbent material on walkways to help identify and limit oil tracking.

Vessel decontamination should occur as close to the recovery area as feasible. In harbors or at docks, containment booms can be deployed. Offshore, barges with containment boom may be used as decontamination platforms. Depending on vessel size, decontamination can occur on the water using skiffs, from docks, or directly from the vessel deck. Smaller vessels can be removed from the water using trailers or cranes and decontaminated on shore within containment.

Ice concentration significantly impacts the feasibility of decontamination methods. High ice concentrations make it difficult to maintain boom containment and may increase risks for smaller skiffs. Managing ice around the decontamination area is critical. Barges or larger vessels can be positioned to deflect ice and create a protected zone on the leeward side. Section 6.2 provides further detail on ice management strategies.

Cold temperatures also complicate vessel decontamination. Heavier oils can become more difficult to remove in freezing conditions. In these scenarios, hot-water pressure washers or steam cleaners have proven effective. Other techniques—such as scraping or wiping with sorbents—can also be used.

Equipment decontamination can be partial or full, depending on the equipment's condition and the spill phase. Whenever possible, keep equipment in the exclusion zone rather than decontaminating it—this reduces waste and the need for extra personnel.

Contaminated equipment still in use usually only needs partial decontamination, removing heavy contamination (like oil dripping from a skimmer) to prevent spreading. Full decontamination is for equipment leaving the exclusion zone, such as when it's released from the response.

Cold-weather and ice-specific considerations for personnel and vessel decontamination also apply to equipment.

6.4.8 In Situ Burning

Background and Experience: While mechanical recovery is typically prioritized or viewed as the default countermeasure in contingency plans, it is not necessarily the most effective way to remove oil quickly from a freshwater environment with ice.

In situ burning (ISB) is an attractive countermeasure option for spills in ice due to its high potential efficiency, rapid removal rate, minimal need for logistics support, and minimal waste generation. Possible localized health hazards can be avoided with proper precautions, specifying safe downwind distances and using SMART monitoring protocol to ensure that air quality remains within established EPA thresholds (ARRT 2008). ISB leaves behind a low toxicity residue on the water or ice surface, which represents a small percentage (often less than 10-20%) of the original oil volume.

ISB is especially suited for use where the presence of even low ice concentrations (below 3/10) can render mechanical recovery techniques with booms and/or skimmers impractical or very ineffective. In sufficient concentrations (6/10 or more), ice can provide a natural barrier to maintain the necessary oil thickness for ignition without the need for containment booms (see discussion in Section 6.3). With less wave action and low temperatures associated with ice environments, the oil remains relatively fresh and unemulsified for a longer period of time (compared to the same oil in open water and more temperate climates). These benefits extend the window of opportunity when successful ignition and burning can take place.

Experience with successful, safe ISB in ice environments encompasses over five decades of research and operational experience including hundreds of laboratory and basin experiments, numerous successful field experiments, large-scale at-sea burns and the unique body of large-scale experience gained through the *Deepwater Horizon* response.

The first recorded use of ISB as an Arctic response countermeasure was in 1958 during a pipeline spill in the Mackenzie River, Northwest Territories, Canada. The USCG carried out important early experimental work burning on sea ice in Alaska (McMinn 1972). A number of large-scale experiments successfully burned up to hundreds of barrels of crude oil that surfaced in spring melt pools after being spilled beneath the ice and trapped through a full winter (NORCOR 1975; Dickins and Buist 1981). In an experimental spill under solid ice in Svalbard in 2006, 28 bbl of crude oil were burned with an overall removal efficiency of 96% after weathering on the ice surface for over one month (Brandvik et al. 2006). Several projects successfully employed burning under field conditions offshore in close pack ice off the Canadian East Coast in 1986 (Figure 6-30) and in the Norwegian Barents Sea in 1993, 2008 and 2009 (Buist and Dickins 1987; Vefsnmo and Johannessen 1994; Sørstrøm et al. 2010).

Historical examples involving successful burning oil spilled from vessels on and in ice include: *Othello/Katelysia,* Sweden 1970; *Imperial St. Clair*, Canada 1979; and the *Edgar Jordain*, Canada 1983. ISB was used successfully offshore in open water on a trial basis during the *Exxon Valdez* oil spill response (Allen 1990).

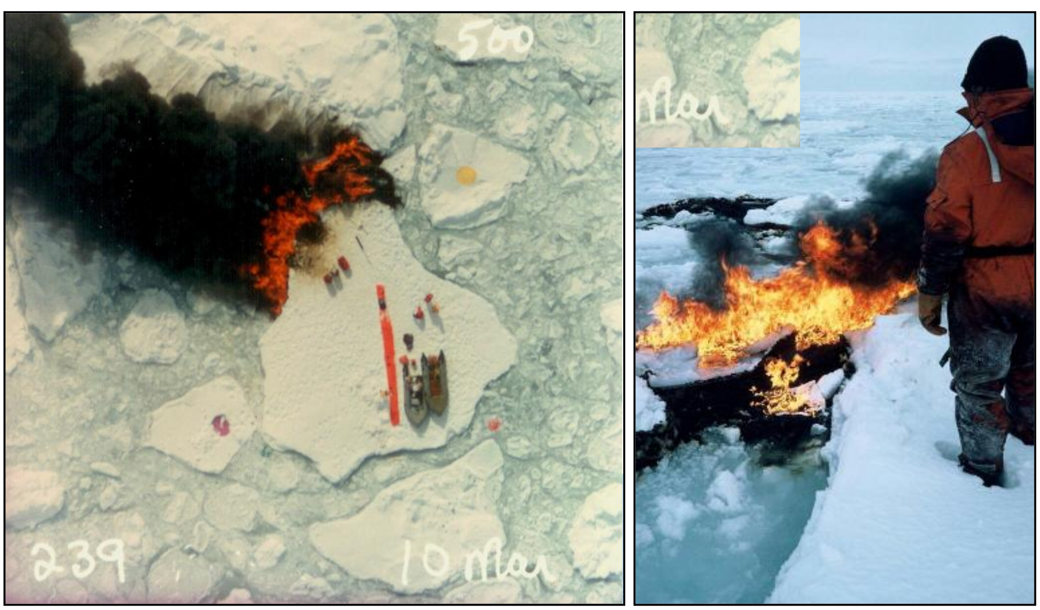


Figure 6-30. Aerial and surface views of burning crude oil spilled in slush between floes in very close pack ice during the 1986 Canadian East Coast "Oil in Pack Ice" experiment (Buist and Dickins 1987). Photos: (Left) R. Belore, SL Ross; (Right) D. Dickins.

The massive ISB operation in response to the *Deepwater Horizon* incident provided a unique set of full-scale operational data. In this first operational, sustained use of ISB offshore on a large scale, approximately 400 controlled burns removed an estimated 220,000 to 310,000 bbl of oil from the Gulf of Mexico (Allen et al. 2011).

Burn Efficiency and Removal Rates: The most important parameter that determines the likelihood of success and expected removal efficiency with ISB is the oil thickness. To achieve 60-80% removal efficiency in most situations, the starting thickness of crude oil needs to be in the order of 0.08-0.2 inches. Removal efficiencies more than 90% are achievable with thick enough oil films. Figure 6-31 graphically shows the principle of burn efficiency, tied to the starting thickness.

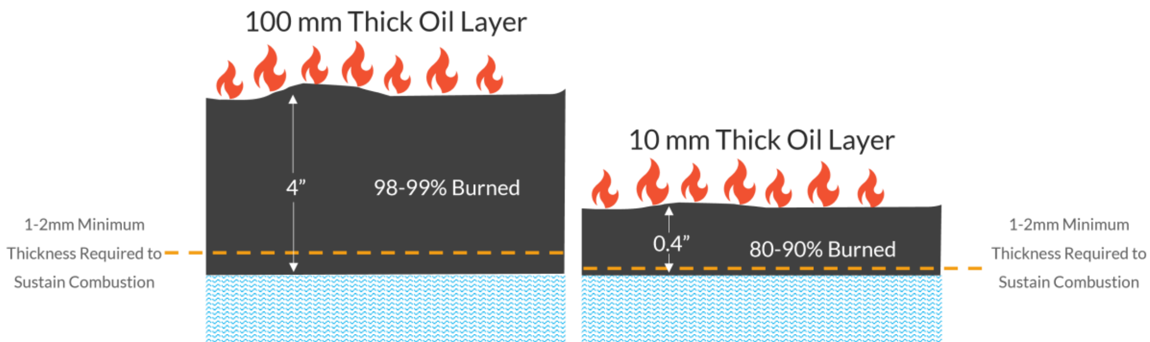


Figure 6-31. The thicker the oil layer, the more efficient the burns will be. Credit: ACS.

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. 2003a):

- Minimum ignitable thickness:
  - 0.04 inches (1 mm) oil thickness for light crudes and gasoline.
  - 0.08-0.2 inches (3-5 mm) oil thickness for weathered crudes and middle-distillates (diesel and kerosene).
  - 0.4 inches (10 mm) oil thickness for residual fuel oils and emulsified crudes.
- The presence of small ice pieces and fragments in the water will affect the burn rate. For a given spill diameter, compared to burning on the water between floes, the burn rate in calm conditions is about halved on relatively smooth frazil/slush ice and halved again on rougher, brash ice. The increased roughness introduced by the ice inhibits flame spreading and increases the vertical heat transfer to the ice compared to open water, in turn leading to a less efficient burn.
- Wave action within the ice also tends to reduce the burn rate. Fortunately, the presence of ice in concentrations high enough to naturally contain the oil also damps wind waves very effectively. Similarly to the effects of rougher ice on burn efficiency, the wave action leads to enhanced heat transfer through the slick and lower burn rates.
- The oil to be ignited should not exceed an emulsification of ~25% water-in-oil, which are generally unignitable. However, some crude oils form mesostable emulsions that remain ignitable even at much higher water contents.
- Ignition is most likely to be successful when winds are below ~19 knots. In certain ice conditions, some wind can be beneficial as it helps concentrate oil into thicker layers. For example, wind

can push oil into open leads or against ice edges, facilitating more efficient burning.

- Cold air temperatures are not generally an impediment to successful ignition. An exception could be with diesel that starts to gel at 10-15°F.

Table 6-3 summarizes burn rates for unemulsified oils spilled on water, given that these "rules of thumb" for ignition and sustained burning are met.

Table 6-3. Summary of in situ burning rates for unemulsified oil spilled on water (Buist et al. 2013).

Oil Type/Condition	Burn/Removal Rate*
Gasoline >0.4 inches (>10 mm) thick	0.2 inches (4.5 mm)/min
Distillate Fuels (diesel and kerosene) >0.4 inches (>10 mm) thick	0.15 inches (4 mm)/min
Crude Oil >0.4 inches (>10 mm) thick	0.14 inches (3.5 mm)/min
Heavy Residual Fuels >0.4 inches (>10 mm) thick	0.08 inches (2.0 mm)/min
Slick 0.2 inches (5 mm) thick**	90% of rate stated above
Slick 0.08 inches (2.0 mm) thick**	50% of rate stated above
* Estimates of burn/removal rate are based on experimental burns and should be accurate to within +/- 20 percent ** Thin slicks will naturally extinguish, so this reduction in burn rate only applies to the end of a burn.	

The following example illustrates how the burn rates can be used in conjunction with the burn diameter (area) to compute the oil volume removed from the surface.

Heavy residual fuel oil is naturally contained in a thick slick by the ice in 7-8/10 concentration. From drone photographs, the contaminated area is estimated at 5,000 square feet (720,000 square inches). The burn naturally extinguishes after 10 minutes with an estimated thickness approximating the thickness required for ignition – 10 mm From Table 6-2 the burn rate is approximately 0.08 inches/minute. The approximate volume removed by burning is estimated as: Burn duration (minutes) x burn removal rate (inches/ minute) x burn area (square inches) or 10 x 0.08 x 720,000 = 576,000 cubic inches or 24,768 US gallons. *Note: Given the variability of burn rate depending on winds, specific oil properties, wave action, oil thickness at time of extinction etc., this estimate should be considered accurate to no better than +/- 20 percent.*

Burning in Different Ice and Snow Conditions

On Ice: Burning pooled oil on solid ice is like burning oil on land in terms of containment and ignition. Oil can spill onto the ice surface from a variety of means, for example, a shoreline tank rupturing, a fuel transfer accident, or a rail car derailment. Oil trapped under ice in the winter can also rise to the surface of rotting ice immediately prior to or during break-up. Oil lying in pools on the ice surface can be ignited in-situ by aerial ignition from a helicopter or by crews on the ice surface if conditions permit.

In addition to oil naturally contained in thick enough films on the ice surface, any oil exposed through the containment tactics discussed in 6.3 is a candidate for burning on site as opposed to skimming, vacuum suction, pumping and transporting to shore. These situations might include oil exposed through air bubbling, trenching, sumps in the ice, etc. (see Section 6.3).

In Snow: Burning oiled snow on top of the ice is possible but can be more challenging to ignite and sustain, with efficiency depending on the oil in snow content. Studies have shown that oiled snow containing up to 70% snow can still burn readily. Successful burns with as little as 3-4% oil content have been achieved by piling oiled snow into hollow cones and igniting from the top. During a series of tests on ice off Prudhoe Bay, Alaska, up to 90% of the oil in contaminated snow was removed through burning, two weeks after the spill (Allen and Nelson 1981). Initiating combustion when oil content is low may require a priming agent such as diesel fuel or gelled gasoline. These tactics generally rely on crews being able to safely venture out onto the ice. In the case where oil is spilled onto the ice surface to produce a thick layer and minimal snow content, it may be possible to carry out aerial ignition remotely from a helicopter without having crews or equipment on the ice.

Among Pack and Drift Ice: Ice concentrations generally need to be 3/10 or less to allow fire booms to be deployed and towed successfully through the ice field without too much interference and maneuvering. When concentrations approach or exceed ~ 6/10, the ice itself starts to provide effective oil containment and maintaining oil in thick enough films for successful ignition without the need for booms. Wind tends to herd the oil, causing it to collect in thicker films against ice edges as it drifts downwind. This natural process further helps with successful ignition and sustaining an efficient burn.

Normally, the goal is to maneuver the booms around ice floes and collect free oil in the boom for subsequent recovery/removal through skimming or burning. In some cases, the goal might be to deliberately collect small pieces of oiled ice within the boom for in situ burning (Figure 6-32).

Potter and Buist (2010) and Potter et al. (2012) reported highly effective (~90%) burning of oil within small ice pieces and brash collected within a fire-resistant boom during the 2009 SINTEF Oil in Ice field experiments in the Norwegian Barents Sea. Ice concentrations in these tests were between 1/10 and 3/10 ice concentration, with large open areas. In the same field project, oil that was allowed to drift and weather while contained naturally in very close pack ice for over a week was also successfully ignited and burned (Sørstrøm et al. 2010).

Depending on the design, fire boom is more prone to damage from wear and use and generally much heavier than conventional open ocean containment boom. Ideally, vessels should have a large open deck area, preferably with a stern roller and hydraulic crane to lift flaked sections of boom into and out of the water.

Figure 6-32. Burning crude oil spilled into a field of ice cakes collected by towing a fire boom through very open drift ice in the Norwegian Barents Sea, 2009 (Potter et al. 2010).

Ignitors: Igniting oil on water among ice or oil and snow on ice can use aerial ignition or hand-deployed, simple-to-fabricate igniters. During the Deepwater Horizon response, igniters deployed from small vessels used an off-the-shelf meltable container preloaded with a gelling agent and mixed with diesel fuel, then ignited using common marine flares.

The Helitorch™ (Figure 6-33) used routinely for decades by the Forest Service was adopted in the 1980s to igniting oil on open water or in ice. These systems are kept in inventory by several response organizations as a primary airborne ignition tool. The Helitorch™ can effectively ignite oil contained within a fireproof boom, oil exposed on top the ice, or naturally contained between floes in thick enough films. An in-depth review of ignitors is discussed in Buist et al. (2016).

ISB Safety and Environmental Issues

Safety: The inter-agency (Alaska Department of Environmental Conservation, USCG, and EPA) In Situ Burning Guidelines (ARRT 2008 Rev. 1) covers operational considerations including personnel safety, and safe distances to ensure protection of the public. While no similar agreement has been made for the Great Lakes, these guidelines provide a baseline and foundational approach.

Burns contained in fire booms are easily extinguished by towing the boom at a higher speed to create oil loss and rapid thinning to below combustible thicknesses. Oil contained naturally between ice floes or in booms will extinguish automatically when the remaining thickness falls below the minimum thickness of 0.04-0.4 inches depending on oil type and degree of weathering. Looking at the burn removal rates shown in Table 6-3, this condition could occur within tens of minutes for most burns. Decades of experience with burning oil on ice in the Canada and Norway have shown that there is negligible loss in ice thickness or ice strength as almost all of the heat is transferred up and out radially from the burning vapor (NORCOR 1975; Dickins and Buist 1981; Brandvik et al. 2006).

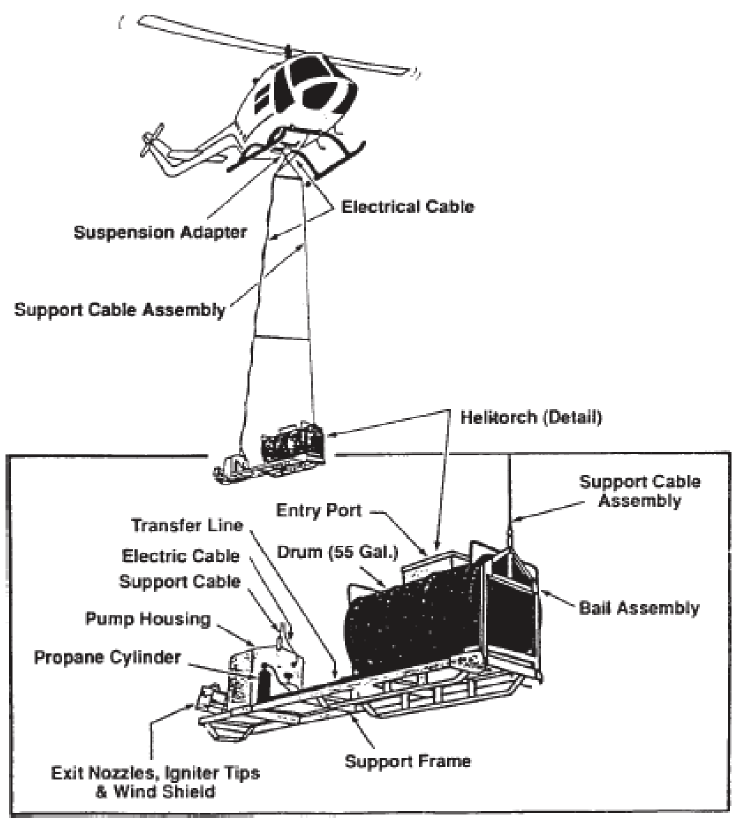


Figure 6-33. Helitorch™ ignition system suspended via helicopter (Buist et al. 2013).

Figure 6-34 shows the safe distance zones prescribed in the Alaska guidelines (ARRT 2008). These guidelines are consistent with the current National Ambient Air Quality Standard of 35 µg/m^3 to ensure public health and safety. When practical, air monitoring (in accordance with the SMART protocols) must be conducted during the burn operation whenever there is a potential of impacting populated areas.

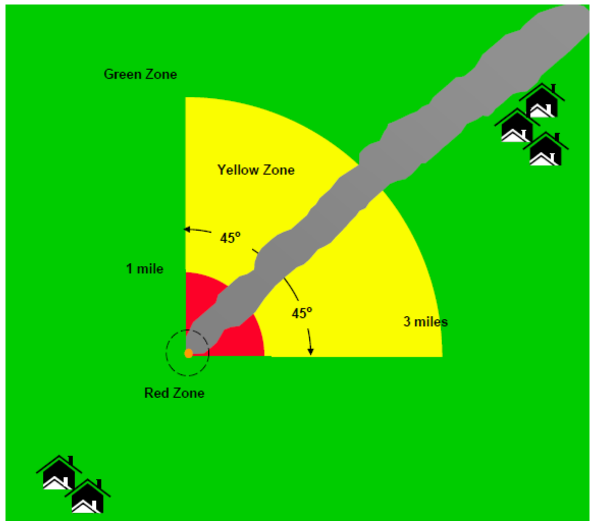


Figure 6-34. Zones for in situ burns on water within 3 miles of shore (ARRT 2008).

In Figure 6-34, the green zone safe distance for burning oil on water more than 3 miles from shore, is 1 mile from populated areas. In these circumstances, the green zone originates immediately after the red zone without a buffering yellow zone. Yellow zones are used only in populated areas where there is potential exposure. The green zone safe distance on land or on water less than 3 miles from shore is 3 miles from populated areas. Burning at a green zone safe distance from populated areas is acceptable following Level 1 public notification. The dashed circle shows an example of a 1,000-ft radius site safety zone for workers that would be determined under a separate site safety plan.

Environmental Impacts: There is a wealth of published environmental information pertaining to the use of ISB as an oil spill countermeasure, in salt as well as fresh water, and in ice. Numerous agencies, primarily in the U.S., have established guidelines for the safe implementation of ISB as a spill countermeasure. For example, the U.S. National Institute of Standards and Technology, NOAA, Environment Canada and the Alaska Regional Response Team have all developed computer models that can be used to predict safe distances for downwind smoke concentrations (see example in Figure 6-34).

The 1993 joint U.S./Canada Newfoundland Oil Burn Experiment provided controlled monitoring results for a large suite of all the critical environmental parameters associated with burning oil, including smoke composition (carcinogens, PAH, etc.), residue toxicity, and upper water-column impacts (Fingas et al. 1995). 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. Scholz et al. (2004) conducted an extensive study of all aspects of ISB as a response tool. That report provides a detailed discussion of field measurements, concluding that surface level particulates and hazardous gas concentrations are below human health levels of concern.

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). In 2021, the Great Lakes National Program Office of the EPA sponsored a review of all aspects of ISB in fresh water (Murphy et al. 2021).

The short-lived smoke plume emitted by a burning oil slick on water is often the main ISB concern to the public and regulators. Concentrations of smoke particles created during the burn typically dissipate to background levels within a few miles downwind (Figure 6-34 and ARRT, 2008).

Concerns are often raised about burn residue, referring to the unburned portion of the original spill remaining on the water surface when the fire extinguishes. Burn residue generally appears as a viscous taffy-like substance that can be picked up in nets or with shovels and pitchforks. Daykin et al. (1994) and Blenkinsopp et al. (1997) reported on burn residue's potential for aquatic toxicity. Bioassays showed very little or no acute toxicity to oceanic organisms for either weathered oil or burn residue. Findings of little or no impact were further 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 U.S. over the past 40 years with a wide range of crudes (Alaska North Slope, Norman Wells, Norwegian, etc.) encountered no instance of residue sinking before it could be recovered**.** 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.*

Concerns are also raised about the perceived long-term environmental consequences, for example, melting ice through soot deposition and air emissions (principally CO_2). Experiences with tracking and documenting downwind deposition to the ice from actual field burns found no measurable 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 also agree with plume modelling and observations of burns at sea (e.g., Fingas et al. 1995).

6.5 Active Monitoring Until Conditions Improve to Allow Recovery

In Arctic regions such as Alaska's North Slope and the Canadian Arctic, nearshore ice conditions are stable for much of the winter, allowing responders to deploy mechanical recovery methods that depend on safely moving responders, vehicles, response gear and heavy equipment on the ice surface, for example: ice cutters, pumps, skimmers, and bobcats and loaders. However, in the Great Lakes Region, ice covering lakes and rivers is much thinner, and less dependable due to the warmer climate, short-term temperature variations, and currents in narrow straits and rivers (Section 2). These conditions can make it unsafe for responders to access spills using traditional mechanical equipment. As a result, direct intervention to respond to a spill may have to wait until conditions stabilize or improve sufficiently to allow safe access.

During these waiting periods, monitoring may be the only response possible. Monitoring includes regular surveillance and sampling to document changes in the contaminated area and oil properties as well as oil movements in mobile pack and drift ice. These data are then used as inputs into oil trajectory and oil weathering models to predict the likely oil fate and environmental effects.

Monitoring can use a mix of technologies and tools as outlined in Sections 5.2 and 5.3 and includes spill tracking and trajectory modeling. By identifying environmental sensitivities in areas most likely to be affected, pro-active protection measures can be initiated to reduce possible impacts.

Section 5.2 discusses the state of the art for oil spill detection, mapping, tracking, and weathering in ice. Two key aspects of these response components are mentioned briefly here as they relate to knowing where the oil is in real time and where it is expected to move in the near term (48-72 hours):

- Tracking buoys
- Trajectory models

Oil spill tracking buoys provide a critical tool for monitoring and response (Figure 6-35). These buoys, equipped with GPS and satellite communication, can track the movement of spilled oil as it moves with the ice in high concentrations or as it moves on the water through ice in low ice concentrations (often at a significantly different speed than the ice itself). Real-time data from the buoys allow for more effective response planning, ensuring resources are deployed where they are most needed once ice conditions improve to allow access. Additionally, integrating buoy data with hydrodynamic, weather and ice models can enhance spill trajectory predictions, improving preparedness and minimizing environmental impact.

Figure 6-35. Examples of relatively low-cost oil tracking buoys suitable for mild to moderate ice conditions. (Figure 5-5 shows a more robust and costly ice buoy designed for Arctic deployment). Photos: ACS.

Ice forecasting models use external climate and position data and algorithms (e.g., oil drift rates as function of wind speed) to predict likely spill trajectories. By using trajectory modeling on a near-real time basis, planners and responders can gain a more thorough understanding of possible oil transport outcomes. Recognizing that even the best forecast models will produce ever larger error bounds after days and weeks, it becomes necessary to reinitialize the oil spill models on a frequent basis (tens of hours to days) with the most accurate real-time spill coordinates available, for example using satellite imagery, airborne surveillance data, or GPS tracking buoys, and updated wind and ocean current forecasts.

The Great Lakes Region employs several advanced models and monitoring systems to observe and predict water and ice conditions, crucial for environmental management, navigation, and resource planning. A key institution in this effort is the NOAA Great Lakes Environmental Research Laboratory (GLERL), headquartered in Ann Arbor, Michigan. GLERL conducts innovative research on the dynamic environments and ecosystems of the Great Lakes and coastal regions.

6.6 Selecting the Most Effective Tactics

The **Great Lakes Oil in Ice is Response Guide** divided into two main parts:

- **Operational Guide** – Contains response checklists for different ice environments and tactic selection "stoplight" charts to help identify viable tactics for a given scenario. Viability is color coded as Likely, Possible, and **Unlikely** without specific regard for response effectiveness. The primary criterion is whether a tactic can be deployed and maintained safety with and without vessel support in a particular combination of ice concentration and thickness.
- **Technical Document** – Provides in-depth information on each topic to support decision-making and execution.

The Operational Guide is intended for use alongside this Technical Document in the following manner:

1. **Determine Operational Need** – Use the operational guide flowchart to identify the appropriate response checklist.
2. **Develop and Execute a Response Plan** – Follow the selected checklist(s) and tactic selection chart to establish an effective plan.
3. **Reference Technical Details** – Use the technical document as needed for detailed guidance when developing and implementing the response plan.

While the two documents are linked (in electronic format) and are intended to be used together, the authors understand that many responders will print and carry the Operational Guide section as a field job aid. Please note that the Operational Guide contains less detail and fewer explanations than the complete Technical Document in order to keep it smaller and more useable in the field, however the two documents are mutually supporting and intended to be used together.

6.7 Cleanup Endpoints

The NOAA Shoreline Assessment Manual (NOAA 2013) provides a hierarchy of cleanup endpoints that have been used extensively for coastal habitats:

- No visible oil
- No more than background
- No longer releases sheens that will affect sensitive areas, wildlife, or human health
- No longer rubs off on contact
- Oil removal to allow recovery without causing more harm than natural removal

As discussed by Whelan et al. (2014), cleanup endpoints for inland oil spills tend to be more stringent than those applied to spills in the marine environment and often require more intensive cleanup methods. The direct human uses of inland habitats, such as drinking water, recreation, industrial use, and irrigation, require a higher degree of treatment than may be required in the marine environment to avoid human health and socio-economic impacts. Inland waters often lack some of the dynamic physical processes (such as waves and tidal fluctuations) that can speed the rate of natural removal of oil residues. Spills near where people live, work, or recreate also often require treatment to a higher level.

Inland spills can affect smaller water bodies where there are slower rates of dilution and degradation. Defining cleanup endpoints for spills in ice conditions are even more challenging because oil can become trapped in ice and snow and then is released during possibly multiple periods of freeze and thaw, releasing often fresh oil. Oil contaminated ice can be transported away from the initial spill area.

Cleanup endpoints should:

- Be clear, concise, and measurable;
- Provide systematic way to evaluate progress and sign treatment areas out of the response;
- Be established early in the response and modified as necessary; and
- Include monitoring to determine effectiveness and effects.

7 References

Alaska Clean Seas. 2015. Alaska clean seas technical manual, volume 1, tactics descriptions. Revision 12, January 2015. http://www.alaskacleanseas.org/tech-manual/.

Alaska Regional Response Team (ARRT). 2008. In-situ burning guidelines for Alaska: Revision 1. Appendix II, Annex F. In: The Alaska Federal/State Preparedness Plan for Response to Oil and Hazardous Substance Discharges/Releases.

Allen, A.A. 1990. Contained controlled burning of spilled oil during the *Exxon Valdez* oil spill. Proceedings 13th Arctic and Marine Oilspill Program (AMOP) Technical Seminar. Environment Canada, Ottawa, Ontario ON, pp. 305-313.

Allen, A.A. and W.G. Nelson. 1981. Oil spill countermeasures in landfast sea ice. Proceedings of the International Oil Spill Conference, API/EPA/USCG, pp. 297-304.

Allen, A.A., D. Jager, N.J. Mabile, and D. Costanzo. 2011. The use of controlled burning during the Gulf of Mexico *Deepwater Horizon* MC-252 oil spill response. Proceedings of the International Oil Spill Conference, American Petroleum Institute, Washington, DC.

API (American Petroleum Institute). 2024. Winter oil spill recovery tactical guidance document: Best practice guidelines for preparedness and response for inland frozen waterways. 29 pp + appendices. https://www.api.org/-/media/pipeline101/resources/winter-oil-spill-recovery-tactical-guidance-document.pdf.

ASTM (American Society for Testing and Materials). 2009. ASTM F2152-standard guide for in-situ burning of spilled oil: Fire-resistant boom. In: Annual Book of ASTM Standards.

Beagle-Krause, C.J., T. Nordam, M. Reed, and R.L. Daae. 2017. State-of-the-art oil spill trajectory prediction in ice infested waters. Proceedings of the International Oil Spill Conference, American Petroleum Institute. https://meridian.allenpress.com/iosc/search-results?page=1&q=State%20of%20the%20art%20oil%20spill%20trajectory&SearchSourceType=1.

Blenkinsopp, S., G. Sergy, K. Doe, G. Wohlgeschaffen, K. Li, and M. Fingas. 1997. Evaluation of the toxicity of weathered crude oil used at the Newfoundland offshore burn experiment (NOBE) and the resultant burn residue. Proceedings 20th Arctic and Marine Oilspill Program (AMOP) Technical Seminar, Environment Canada, Ottawa, ON, 677-684.

Bradford, J.H., D.F. Dickins, and P.J. Brandvik. 2010. Detection of snow-covered oil spills on sea ice using ground-penetrating radar. Geophysics 75:G1-G12, doi: 10.1190/1.3312184. https://scholarworks.boisestate.edu/cgi/viewcontent.cgi?article=1045&context=cgiss_facpubs.

Brandvik, P.J. and L-G. Faskness. 2009. Weathering processes in Arctic oil spills: Meso-scale experiments with different ice conditions. Cold Regions Science and Technology 55:160-166. https://www.sciencedirect.com/science/article/abs/pii/S0165232X08000992?via%3Dihub.

Brandvik, P.J. and T. Buvik. 2009. Using dogs to detect oil hidden in snow and ice--Results from field training on Svalbard April 2008. https://www.sintef.no/globalassets/project/jip_oil_in_ice/dokumenter/publications/jip-rep-no-14-oildog-snow-ice.pdf.

Brandvik, P.J., L-G. Faksness, D.F. Dickins, and J. Bradford. 2006. Weathering of oil spills under Arctic conditions: Field experiments with different ice conditions followed by in-situ burning. Presented at the 2006 Third Annual NATO/CCMS Oil Spill Response Workshop, Oct 11-13, Dartmouth, NS, Canada.

Buist, I. and D. Dickins. 1987. Experimental spills of crude oil in pack ice. Proceedings International Oil Spill Conference. American Petroleum Institute. Washington DC, pp. 373-381.

Buist, I. and K. Trudel. 1995. Laboratory studies of the properties of in-situ burn residues. Technical Report Series 95-010, Marine Spill Response Corporation, Washington, DC, 110 pp.

Buist, I., D. Dickins, L. Majors, K. Linderman, J. Mullin, and C. Owens. 2003a. Tests to determine the limits to in-situ burning in brash and frazil ice. Proceedings 26th Arctic and Marine Oilspill Program (AMOP) Technical Seminar, Vol. 2, Environment Canada, Ottawa ON, 629-648.

Buist, I.A., T. Coe, D. Jensen, S. Potter, L. Anderson, K. Bitting, and K. Hansen. 2003b. In-Situ burn operations manual. U.S. Coast Guard Research and Development Center Report CG-D-06-03, Groton, CT.

Buist, I., R. Belore, D. Dickins, A. Guarino, D. Hackenberg, and Z. Wang. 2009. Empirical weathering properties of oil in ice and snow. Proceedings 32nd Arctic and Marine Oilspill Program Technical Seminar, Vol. 1, Environment Canada, Ottawa ON, pp. 67-107. https://www.researchgate.net/publication/264875006_Empirical_Weathering_Properties_of_Oil_in_Ice_and_Snow.

Buist, I.A., S.G. Potter, B.K. Trudel, S.R. Shelnutt, A.H. Walker, D.K. Scholz, P.J. Brandvik, J. Fritt-Rasmussen, A.A. Allen, and P. Smith. 2013. In situ burning in ice-affected waters: State of knowledge report - Final report 7.1.1 to the Arctic Response Technology Joint Industry Programme. Available along with two companion reports on ISB at http://www.arcticresponsetechnology.org/.

Buist, I., S. Potter and P. Lane. 2016. Historical review of the state of the art for oil slick ignition for ISB. Final report to the IOGP Arctic Oil Spill Response Technology JIP, 44 pp. https://www.arcticresponsetechnology.org/wp-content/uploads/2017/09/Igniters-Report-Final.pdf.

Davenport, A.C., K. Anania, S.A. Resetar, A. Levedahl, L. McLane, J. Caulkins, and M. Bauman. 2024. Great Lakes oil spill response capabilities evaluation. Homeland Security Operational Analysis Center. https://www.rand.org/pubs/research_reports/RRA2375-1.html.

Daykin, M., G.A. Sergy, D. Aurand, G. Shigenaka, Z. Wang, and A. Tang. 1994. Aquatic toxicity resulting from in-situ burning of oil-on-water. Proceedings of the 17th Arctic and Marine Oilspill Program (AMOP) Technical Seminar, Environment Canada, Ottawa, Ontario, pp. 1165-1193.

Department of Transportation Government of the Northwest Territories (NWT). 2015. Guidelines for safe ice construction, Yellowknife, NWT. Prepared under contract by NOR-EX Ice Engineering Inc. https://www.inf.gov.nt.ca/sites/inf/files/resources/0016-001_norex_ice_road_constr._web.pdf.

Dickins, D.F. 2011. Behavior of oil spills in ice and implications for Arctic spill response. Paper No. OTC22126, Proceedings Arctic Technology Conference, Houston TX. https://dfdickins.com/pdf/OTC22126LR.pdf.

Dickins, D.F. 2000. Detection and tracking of oil under ice. Report prepared for the US Department of Interior, Minerals Management Service, Herndon VA. https://www.bsee.gov/sites/bsee.gov/files/osrr-oil-spill-response-research/348aa.pdf

Dickins, D.F. and J.H.S. Andersen. 2009. Remote sensing technology review and screening. Oil in Ice—JIP, Report 22. SINTEF Materials and Chemistry, Marine Environmental Technology. https://www.researchgate.net/publication/289680038_Remote_sensing_for_the_oil_in_ice_joint_industry_program_2007-2009.

Dickins, D.F. and I.A. Buist. 1981. Oil and gas under sea ice study: Vols. I & 2. Prepared by Dome Petroleum Ltd. for COOSRA, Report CV-1, Calgary, AB, Canada.

Dickins, D., P.J. Brandvik, J. Bradford, L-G. Faksness, L. Liberty, and R. Daniloff. 2008. Svalbard 2006 experimental oil spill under ice: Remote sensing, oil weathering under Arctic conditions and assessment of oil removal by in-situ burning. Proceedings of the International Oil Spill Conference, American Petroleum Institute, Washinton, DC. https://meridian.allenpress.com/iosc/article/2008/1/681/202849/SVALBARD-2006-EXPERIMENTAL-OIL-SPILL-UNDER-ICE.

Enbridge. 2018. Inland spill response tactics guide. Enbridge Pipelines, Inc. https://www.enbridge.com/Projects-and-Infrastructure/Public-Awareness/Emergency-Response-Action-Plans/Inland-Spill-Response-Tactics-Guide.

Fingas, M.F. and C.E. Brown. 2014. Review of oil spill remote sensing. Marine Pollution Bulletin 83:9-23. https://www.sciencedirect.com/science/article/abs/pii/S0025326X14002021.

Fingas, M.F., G. Halley, F. Ackerman, R. Nelson, M.C. Bissonnette, N. Laroche, Z. Wang, P. Lambert, K. Li, P. Jokuty, G. Sergy, W. Halley, J. Latour, R. Galarneau, B. Ryan, P.R. Campagna, R.D. Turpin, E.J. Tennyson, J. Mullin, L. Hannon, D. Aurand and R. Hiltabrand. 1995. The Newfoundland offshore burn experiment. Proceedings International Oil Spill Conference, American Petroleum Institute, Washington, DC, pp. 123-132.

Fitzgerald, A. and W.J. van Rensburg. 2024. Limitations of Gold's formula for predicting ice thickness requirements for heavy equipment. Canadian Geotechnical Journal 61(1):183-188. https://doi.org/10.1139/cgj-2022-0464.

GLERL (Great Lakes Environmental Research Laboratory). 2024. Overview of NOAA's Great Lakes ice products. https://www.weather.gov/news/242509-great-lakes-ice.

Gulec, I. and D.A. Holdway. 1999. The toxicity of laboratory burned oil to the amphipod *Allorchestes compressa* and the snail *Polinices conicus*. Spill Science & Technology Bulletin 5:135-139.

Hansen, K.A. and M. Fitzpatrick. 2017. Federal On Scene Coordinator (FOSC) guide for oil in ice. USCG Research and Development Center, Report No. CG-D-01-18, New London, CT.

https://homeport.uscg.mil/Lists/Content/Attachments/43701/USCG%20FOSC%20Guide%20-%20Oil%20in%20Ice.pdf.

Hansen, K.A. and M. Fitzpatrick. 2018. Oil in ice project final report. USCG Research and Development Center, Report No. CG-D-01-18, New London, CT. https://apps.dtic.mil/sti/trecms/pdf/AD1050443.pdf.

International Association for Great Lakes Research. 2024. LAKES Letter FALL 2024, No. 23. https://iaglr.org/ll/2024-4_Fall_LL23.pdf.

IISD (International Institute for Sustainable Development). 2025. Oil detection canines. Poster presentation at the Alaska Forum on Environment, Anchorage.

Lamie, N., L. Zabilansky, and A. Stott. 2020. Methods to enhance mechanical recovery in arctic conditions. Hanover, NH: US Department of the Interior, Bureau of Safety and Environmental Enforcement. BSEE 2020-01-01.

Lee, K., Z. Li, B. Robinson. P.E. Kepkay, M. Blouin and B. Doyon. 2011. Field trials of in-situ oil spill countermeasures in ice-infested waters. International Oil Spill Conference, American Petroleum Institute, Washington, DC, 16 pp.

Leifer, I., W.J. Lehr, D. Simecek-Beatty, E. Bradley, R. Clark, P. Dennison, Y. Hu, S. Matheson, C.E. Jones, B. Holt, M. Reif, D.A. Roberts, J. Svejkovsky, G. Swayze, and J.I. Wozencraft. 2012. State of the art satellite and airborne marine oil spill remote sensing: Application to the BP *Deepwater Horizon* oil spill. Remote Sensing of Environment 124:185-209. https://www.sciencedirect.com/science/article/abs/pii/S0034425712001563.

McMinn, T.J. 1972. Crude oil behavior on Arctic winter ice: Final report. Office of Research and Development, United States Coast Guard, Project 734108, Washington, DC, NTIS Publication No. AP-754, 261 p.

Pegau, W.S., J. Garron, and L. Zabilansky. 2016.Detection of oil on-in-and-under ice–Final report 5.3." Arctic Response Technology Joint Industry Project.

Pegau, W.J., J. Garron, L. Zabilansky, and 19 other authors. 2017. Detection of oil in and under ice. Proceedings of the International Oil Spill Conference*,* Washington, DC, pp. 1857–1876 https://meridian.allenpress.com/iosc/article/2017/1/1857/197736/Detection-of-oil-in-and-under-ice.

Mason, L., C. Riseng, A. Gronewold, E. Rutherford, J. Wang, A. Clites, S. Smith, and P. McIntyre. 2016. Fine-scale spatial variation in ice cover and surface temperature trends across the surface of the Laurentian Great Lakes. Climatic Change 138, doi: 10.1007/s10584-016-1721-2. https://owl.cwp.org/mdocs-posts/fine-scale-spatial-variation-in-ice-cover-and-surface-temperature-trends-across-the-surface-of-the-laurentian-great-lakes/.

MANICE (Manual of Ice). 2005. Manual of standard procedures for observing and reporting ice conditions. Canadian Ice Service. https://www.canada.ca/en/environment-climate-change/services/weather-manuals-documentation/manice-manual-of-ice.html.

Murphy, E.A., B.S. Adewale, H.V. Pham, J. Aurell, B.K. Gullett, K.S. Arsava, N.J. Lamie, M.A. Wurl, M.M. Cisternelli, and M. Fitzpatrick. 2021. Freshwater in-situ oil burning. Report No. CG-D-01-21. USCG R&D Center, Groton CT. https://apps.dtic.mil/sti/pdfs/AD1124052.pdf

NORCOR. 1975. The interaction of crude oil with Arctic Sea ice. Beaufort Sea Project Technical Report No. 27, Canadian Department of Environment, Victoria, BC, Canada.

NOAA, 2013. Shoreline assessment manual 4th Ed. https://response.restoration.noaa.gov/sites/default/files/manual_shore_assess_aug2013.pdf.

Owens, E. and D. Dickins. 2015. Guide to oil spill response in snow and ice conditions. Prepared for the EPPR working group of the Arctic Council, Tromso, Norway. https://oaarchive.arctic-council.org/items/dbf994b2-7e93-48dc-8ee6-642facdf0687.

Potter, S. and I. Buist. 2010. In-situ burning in Arctic and ice-covered waters: Tests of fire-resistant booms in low concentrations of drift ice. Proceedings 33rd Arctic and Marine Oilspill Program Technical Seminar, Environment Canada, Ottawa, ON, pp. 743-754.

Potter, S., I. Buist, K. Trudel, D. Dickins, and E. Owens. 2012. Spill response in the Arctic offshore. Prepared for the American Petroleum Institute and the Joint Industry Programme on Oil Spill Recovery in Ice, D. Scholz (ed.). American Petroleum Institute, Washington DC, 157 pp.

Scholz, D., S.R. Warren Jr., A.H. Walker, and J. Michel. 2004. In-situ burning: The fate of burned oil. American Petroleum Institute (API) Publication 4735.

Schwab, D.J. 2016. Statistical analysis of Straits of Mackinac line 5 worst case scenarios. University of Michigan Water Center, Ann Arbor.

S.L. Ross Environmental Research Ltd. 2002. Identification of oils that produce non-buoyant in situ burning residues and methods for their recovery. API Publ. No. DR145, American Petroleum Institute, Washington, DC.

Song, Y., A. Fujisaki-Manome, C.H. Barker, A. MacFadyen, J. Kessler, D. Titze, and J. Wang. 2024. Modeling study on oil spill transport in the Great Lakes: The unignorable impact of ice cover. Journal of Environmental Management 358:120810. https://www.sciencedirect.com/science/article/pii/S0301479724007965.

Sørstrøm, S.E., P.J. Brandvik, I. Buist, P. Daling, D. Dickins, L-G. Faksness, S. Potter, J.F. Rasmussen, and I. Singsaas. 2010. Joint industry program on oil spill contingency for Arctic and ice-covered waters: Summary report. Oil in Ice JIP Report No. 32, SINTEF, Trondheim, Norway. www.sintef.no/Projectweb/JIP-Oil-In-Ice/Publications/.

Vefsnmo, S. and B. Johannessen. 1994. Experimental oil spill in the Barents Sea - Drift and spread of oil in broken ice. Proceedings 17thArctic and Marine Oilspill Program Technical Seminar, Vol. 1, Environment Canada, Ottawa ON, pp. 355-370.

Whelan, A., G. Andrews, J. Clark, J. Michel, and B. Benggio. 2014. Developing cleanup endpoints for inland oil spills. Proceedings of the International Oil Spill Conference, American Petroleum Institute, Washington, DC, pp. 1267-1280. https://meridian.allenpress.com/iosc/article/2017/1/1770/198007/Options-for-Minimizing-Environmental-Impacts-of.

Wilkinson, J.P., T. Boyd, B. Hagen, T. Maksym, S. Pegau, C. Roman, H. Singh and L. Zabilansky. 2015. Detection and quantification of oil under sea ice: The view from below. Cold Regions Science and Technology 109:9-17. https://www.sciencedirect.com/science/article/pii/S0165232X14001372.

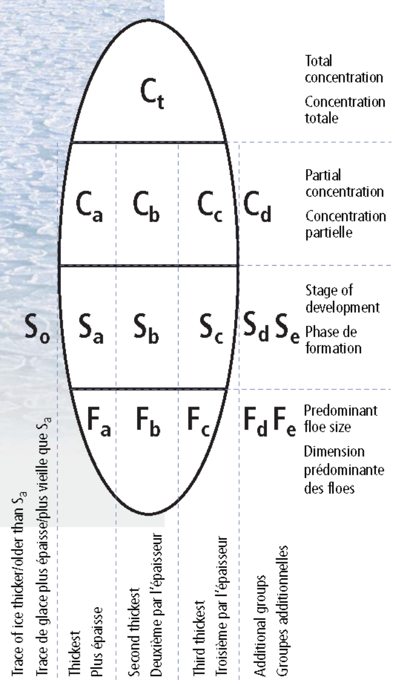
Appendix A: Fact Sheet: Lake Ice Symbols

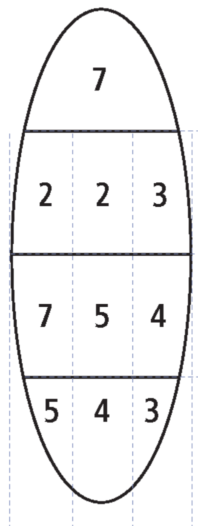
Environment Canada / Environnement Canada

FACT SHEET / FICHE D'INFORMATION

LAKE ICE SYMBOLS
SYMBOLES DE LA GLACE D'EAU DOUCE

2020





Total concentration: the ice coverage of an area determined by its concentration and expressed in tenths (this example, 7/10)
Concentration totale : l'étendue de la couverture de glace, exprimée en dixièmes de la superficie du secteur (cet exemple, 7/10).

Partial concentration: the break-down of the total ice coverage expressed in tenths and graded by thickness. The thickest starting from the left and in this example, 2/10 is the thickest.
Concentration partielle : les concentrations respectives, exprimées en dixièmes, des glaces de différente épaisseur, par ordre décroissant. La plus épaisse commence à la gauche du diagramme, c'est-à-dire, 2/10 est le plus épais.

Stage of development: the type of ice in each of the grades determined by its age, that is, 2/10 is thick lake ice (7), 2/10 is medium lake ice (5) and 3/10 thin lake ice (4).
Stade de développement : le type de glace de chacune des catégories déterminé par son âge, c'est-à-dire, 2/10 est de la glace de lac épaisse (7), 2/10 est de la glace de lac moyenne (5), et 3/10 est de la glace de lac mince (4).

Floe size: the form of the ice determined by the dominant floe size for each section. In this example, big floes (5) for thick lake ice (7); medium floes (4) for medium lake ice (5); and small floes (3) for thin lake ice (4).
Taille des floes : la forme de la glace, déterminée par la taille des floes dominants de chaque section. Dans cette exemple, grands floes (5) pour la glace de lac épaisse (7); floes moyens (4) pour glace de lac moyenne (5) et petits floes (3) pour glace de lac mince (4).

LAKE ICE SYMBOLS/SYMBOLES DE LA GLACE D'EAU DOUCE

Stage of Development/Stade de développement ($S_oS_aS_bS_cS_dS_e$)

Description/Élément	Thickness/Épaisseur	Code
New ice/Nouvelle glace	<5 cm	1
Thin lake ice/Glace de lac mince	5-15 cm	4
Medium lake ice/Glace de lac moyenne	15-30 cm	5
Thick lake ice/Glace de lac épaisse	30-70 cm	7
Very thick lake ice/Glace de lac très épaisse	>70 cm	1•
Undetermined, unknown or no form/ Indéterminée, inconnue ou sans forme		X

Floe Size/Grandeur des floes ($F_aF_bF_c$)

Description/Élément	Width/Extension	Code
Pancake ice/Glace en crêpes		0
Small ice cake, brash ice/Petit glaçons, sarrasins	<2 m	1
Ice cake/Glaçons	2-20 m	2
Small floe/Petits floes	20-100 m	3
Medium floe/Floes moyens	100-500 m	4
Big floe/Grands floes	500-2000 m	5
Vast floe/Floes immenses	2-10 km	6
Giant floe/Floes géants	>10 km	7
Fast ice/Banquise côtière		8
Undetermined, unknown or no form/ Indéterminée, inconnue ou sans forme		X
Strips (concentration = C)/ Glace en cordons (concentration = C)		∽ C

Canadian Ice Service/Service canadien des glaces (CIS/SCG)

Client Services/Service à la clientèle
Ottawa, Ontario
K1A 0H3

Email/Courriel: cisclients-scgclients@ec.gc.ca
Web site/Site web: https://www.canada.ca/en/environment-climate-change/services/ice-forecasts-observations.html

Canada

Environment Canada / Environnement Canada

LAKE ICE SYMBOLS
SYMBOLES DE LA GLACE D'EAU DOUCE

WMO Concentration Colour Code – Lake Ice
Code de couleurs de l'OMM – Concentration – Glace d'eau douce

- Ice Free / Libre de glace
- < 1/10
- 1-3/10
- 4-6/10
- 7-8/10
- 9-10/10
- Fast Ice / Banquise côtière
- ??? Undefined / Glace non définie

Colour is based on total ice concentration.
La couleur utilisée est établie en fonction de la concentration totale de la glace.

Concentration of Ice
Concentrations de glace

<1/10	Open water/ Eau libre
1–3/10	Very open drift/ Banquise très lâche
4–6/10	Open drift/ Banquise lâche
7–8/10	Close pack/Drift Banquise serrée
9/10	Very close pack/ Banquise très serrée
9+/10	Very close pack/ Banquise très serrée
10/10	Compact/Consolidated ice Banquise compact/consolidée

WMO Stage of Development Colour Code – Lake Ice
Code de couleurs de l'OMM – Stade de développement – Glace d'eau douce

- Ice Free/Libre de glace
- Open Water/Eau libre
- New Ice/Nouvelle glace *<5 cm*
- Thin Ice/Glace mince *5-15 cm*
- Medium Ice/Glace moyenne *15-30 cm*
- Thick Ice/Glace épaisse *30-70 cm*
- Very Thick Ice/Glace très épaisse *> 70 cm*
- Fast Ice/Banquise côtière
- ??? Undefined Ice/Glace non-définie

Colour is based on stage of development of predominant ice.
La couleur utilisée est établie en fonction du stade de développement de la glace prédominante.

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