Oil Spill Response Mechanical Recovery Systems for Ice-Infested Waters: Examination of Technologies for the Alaska Beaufort Sea

Report to
Alaska Department of Environmental Conservation

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Cover Photo: Spring ice melting in Beaufort Sea (from NOAA gallery of arctic images)

Executive Summary

This report has been developed for the Alaska Department of Environmental Conservation (ADEC) by Nuka Research and Planning Group, LLC (Nuka Research) to research and evaluate oil spill response mechanical recovery systems for ice-infested waters. The purpose of this report is to provide information and analysis that may be applied to improve oil spill response effectiveness on the Alaskan North Slope Beaufort Sea by identifying the existing state-of-technology for mechanical recovery in sea ice, and investigating any new mechanical recovery systems that may be transferable for use in ice-infested waters.

The coastline of the Beaufort Sea near Prudhoe Bay is a particularly challenging operating environment characterized by a coastal wetland and a shallow nearshore area inside a series of barrier islands. Water depths of less than six feet extend as far as two miles offshore and water depths of less than twelve feet extend as far as five miles offshore. Because of the extremely shallow nearshore water depths, the deployment and operation of many mechanical recovery technologies may be limited by vessel access to these shallow areas. Sea ice further complicates oil spill response operations, particularly during fall freeze-up and spring break-up.

Because of the variation in water depth and the range of ice conditions possible in nearshore and offshore areas as ice season progresses, spill recovery technologies must be adaptable to a range of conditions. Deployment and operation will be effected both by the ability of the equipment to function within the range of ice conditions encountered, and the ability of vessels to deploy and tend the equipment at the appropriate water depth and under the same range of ice conditions.

Any discussion of oil spill recovery technologies and capabilities must recognize the more pragmatic considerations that drive equipment stockpiles in the North Slope and other regions. When an operator or response organization purchases new equipment, it is often to replace older equipment that has been amortized or phased out. The report identifies several areas in state regulations and policy that could be interpreted as promoting or requiring improved mechanical recovery technologies for ice-infested waters.

State regulations (18 AAC 75.447) require that ADEC "review and appraise technology applied at other locations in the United States and the world that represent alternatives to the technologies used by plan holders in their oil discharge prevention and contingency plans submitted to meet response planning standards in 18 AAC 75.430 - 18 AAC 75.442 and the performance standards of 18 AAC 75.005 - 18 AAC 75.080." State BAT regulations at 18 AAC 75.445(k)(1) indicate that ADEC will consider a specific response technology to be BAT if "the technology of the applicant's oil discharge response system as a whole is appropriate and reliable for the intended use as well as the magnitude of the applicable response planning standard." This means that response technologies, systems, and tactics that are intended to meet the response planning standard

(RPS) in Beaufort Sea ice conditions must be "appropriate and reliable" for use under those conditions.

This report considers the appropriateness and reliability of a range of technologies that may be used in the nearshore and offshore Beaufort Sea environments during ice season. Five categories of mechanical response technologies are considered: containment, recovery, ice processing, ice management, and pumping. The report reviews the state-of-technology for mechanical recovery of oil in ice-infested waters by considering market-ready technologies that are in use in arctic regions, including the Alaska Beaufort Sea, based on manufacturers' specifications, published literature, and oil spill equipment reference manuals. The report includes a discussion of experimental technologies that have been developed or tested for use in ice-infested waters and considers the current status of international research and development efforts. Since most of the information in this report is based on review of print materials, it is important that ADEC follow up with equipment tests and trials to better understand the capabilities and limitations of some of the systems discussed.

This report includes a technology analysis (as specified in 18 AAC 75.447(a)(2)) to compare and contrast the capabilities of mechanical recovery technologies currently stockpiled in Alaska with the existing and experimental technologies described in the report. This analysis uses the best available technology (BAT) criteria established in state regulations at 18 AAC 75.445(k)(3) (with the exception of cost, which is not considered) and considers applicability both to the nearshore and offshore Beaufort Sea environments (as authorized under 18 AAC 75.447(b)). This report **does not** constitute a findings document under 18 AAC 75.447, although it does present recommendations for how ADEC might proceed in developing a findings document.

This report concludes that there are no novel concepts in containment boom technology, although research and development in this area continue to focus on winterization of existing technologies. There is only one ice-capable open water containment boom on the market that is not currently stockpiled on the North Slope (Norlense), and there is not enough data to definitively recommend this boom, which does not appear in the 2004/2005 "World Catalog of Oil Spill Response Products," over the boom currently in use in the Beaufort Sea, but it should be considered. Several manufacturers offer protected water booms with high tensile strength that may be suitable for use when sea ice is present in the nearshore Beaufort Sea. Since these booms are smaller and lighter and may be easier to deploy from shallow-draft vessels, they should be tested in the Beaufort Sea ice conditions.

This report shows that there are a few arctic skimmers currently on the market that are not stockpiled in Alaska, and recommends that these ice-capable skimmers be tested in the Beaufort Sea since many are appropriate for nearshore deployment. Most ice-capable skimmers operate in stationary mode in leads with lower ice concentrations; they are differentiated from other non-ice stationary skimmers by enhanced ice-processing capabilities. In terms of specific skimmer

models, the Lamor LRB shows the most promise for use on the North Slope because it works well in ice conditions and is easily positioned using a crane or hydraulic arm.

This report recommends close monitoring of the novel skimmer surface concept under development at UCSB. Earlier tests of the novel skimmer surfaces in open water (at Ohmsett) showed that, by tailoring the skimmer surface to the oil properties, recovery could be enhanced by as much as 50%. Preliminary results from basin trials held in March 2007 suggest that the technology may also provide enhanced recovery in certain ice conditions. This technology may offer another option for recovery of oil in ice-infested waters by allowing responders to tailor the skimmer surface to the type of oil spilled and possibly the type and characteristics of sea ice present.

Several ice processing technologies have been developed and put to use in Finland, but none are in use in the Beaufort Sea. This report recommends that one or more of these technologies should be tested in the Beaufort Sea to determine whether they offer improved mechanical recovery efficiencies. However, since these technologies require large vessels to deploy them, they may not be appropriate for nearshore response in shallow areas.

This report strongly recommends that ice management techniques be practiced and tested in the Beaufort Sea. Since ice management is more a tactical issue than technological, it can be effectively practiced without the use of oil or simulated oil. Moreover, earlier field trials in the Beaufort showed that effective ice management could expand the operating window for mechanical recovery to higher ice concentrations. At present, ACS does not have established ice management tactics or equipment, although some of their oil booming equipment and tactics could be modified for ice management. However, it may be advisable to stock purpose-built ice boom to improve ice management and maximize the opportunity for on-water recovery. Future field trials and training courses should consider the use of ice boom in varying configurations as a method to enhance mechanical recovery. Ice deflection technologies and vessel ice management tactics should also be explored.

This report concludes that positive displacement Archimedes screw auger pumps are the favored technology for viscous oils in ice, and the pumps in stock on the North Slope are comparable to others on the market. The report recommends that North Slope operators' BAT analyses consider whether certain new pump models offer enhanced capabilities due to their integrated annular injection systems.

In addition to the five types of mechanical recovery equipment and systems described in the report, recommendations are also made regarding other issues related to the mechanical recovery of oil spills in ice. The report emphasizes that the limitations of a mechanical recovery system in arctic conditions may not always result from a technological limit or deficiency, but from other operational, logistical, and safety considerations. Efforts to improve mechanical recovery

capabilities should also factor in these considerations.

A major challenge in responding to oil spills in ice-infested waters is the scale of the response. Many of the technologies (particularly skimmers) that show promise for use in ice-infested waters are meant for batch recovery of contained oil in pits or ice leads, not for large-scale, high capacity recovery. Researchers should continue to consider ways to implement these technologies on a larger scale.

Based on extensive literature review, this report concludes that the emphasis among researchers in the oil spill response field who are addressing arctic oil spills seems to be on non-mechanical recovery. It is important that agencies such as ADEC, who favor mechanical recovery over chemical countermeasures, continue to advocate for research and development into new technologies. Other U.S. agencies and funding sources should also acknowledge this need and promote additional study of mechanical recovery technologies.

Finally, in considering whether technologies are "appropriate and reliable" for use in Beaufort Sea ice conditions, it is important to account for the range of conditions that may be encountered. Ice conditions in the Beaufort Sea are highly dynamic during freeze-up and break-up, both over time and in different environments. At the same time, different mechanical recovery technologies and systems may be particularly suited to a certain range of ice conditions. This can create a problem not only in stocking equipment, but in selecting and deploying the appropriate technologies for the ice conditions. To a certain degree, arctic response organizations should have some variability in their equipment inventory to address the changing parameters of the ice environment.

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1. Introduction

1.1 Purpose

This report has been developed for the Alaska Department of Environmental Conservation (ADEC) by Nuka Research and Planning Group, LLC (Nuka Research) to research and evaluate oil spill response mechanical recovery systems for ice-infested waters. The purpose of this report is to provide information and analysis that may be applied to improve oil spill response effectiveness on the Alaskan North Slope Beaufort Sea by identifying the existing state-of-technology for mechanical recovery in sea ice, and investigating any new mechanical recovery systems that may be transferable for use in ice-infested waters.

1.2 Scope

The report reviews the state-of-technology for mechanical recovery of oil in ice-infested waters by considering market-ready technologies that are in use in arctic regions. Section 1 provides brief overview of the Beaufort Sea operating environment and specific considerations for deployment and effectiveness of mechanical recovery equipment. The report then reviews the equipment and systems currently stockpiled in Alaska for use in the Beaufort Sea. Section 2 reviews specific technologies in use in Alaska and other arctic nations, and also describes experimental technologies as reported in English-language literature. The analysis of each technology considers the potential impacts of ice conditions and nearshore vs. offshore operating environments, and also considers how the size and configuration of certain equipment affect its suitability for deployment from smaller vessels operating in the nearshore shallows. The report includes a discussion of experimental technologies that have been developed or tested for use in ice-infested waters and considers the current status of international research and development efforts.

Section 3 contains a comparative analysis of the mechanical recovery technologies described in Section 2, to contrast the capabilities of mechanical recovery technologies currently stockpiled in Alaska with the existing and experimental technologies described in the report. This analysis uses the best available technology (BAT) criteria established in state regulations at 18 AAC 75.445(k)(3).

Section 4 provides recommendations for improving mechanical recovery capabilities under Beaufort Sea ice conditions, and highlights specific equipment and technologies that should be considered for testing or stockpiling on the North Slope.

This report presumes that the reader is familiar with the basics of oil spill response technologies and the general considerations for deploying spill response equipment in the presence of sea ice. However, additional background information is presented in appendices to this report. Appendix A reviews the characteristics and formation of sea ice and discusses how sea ice conditions may impact oil behavior and movement. Appendix B presents a basic categorization scheme for the mechanical oil spill recovery technologies and equipment that may be used to clean up oil spills in ice-infested waters. Appendix C includes a list of acronyms and abbreviations.

1.3 Considerations for Mechanical Recovery of Oil Spills in Ice-infested Waters

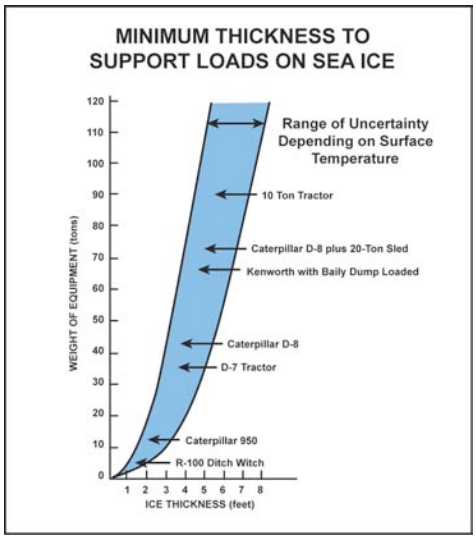
Most technologies used in responding to oil spills in sea ice have been adapted from those typically used on open water and land. While some on-water response technologies may be transferable to open water arctic conditions, sea ice has been demonstrated to reduce the efficiency of many response methods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

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

The formation, thickness, and percentage of ice coverage all affect the selection of response technologies, as do the characteristics of the spilled oil, which can be impacted by sea ice. Fast ice is often considered a favorable condition for mounting spill response operations, because equipment and personnel can be deployed from the ice. However, this requires sufficient ice thickness to support equipment and personnel.

Pack ice can sometimes be thick enough to support ground transport or helicopters as well. However, even if pack ice is sufficiently thick to support heavy equipment, it may still move unpredictably, making response operations unsafe. Figure 1 shows the minimum required ice thickness to support a range of heavy equipment.

Figure 1. Ice Load Requirements. (ACS, 2003)



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

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

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

1.4 Application of Mechanical Recovery Technologies in the Beaufort Sea

1.4.1 BEAUFORT SEA OPERATING ENVIRONMENT AND ICE CYCLES

The Beaufort Sea environment varies widely from the shallow protected waters within the barrier island system to the deeper and more open water environment. Sea ice is present in the Beaufort for about 9 months every year, and its formation and break-up follow a seasonal pattern. Fall freeze-up begins in early October, with the formation of grease or frazil ice in the nearshore areas. The ice formation progresses from shallow nearshore areas seaward, with the ice coverage increasing in area and thickness until stable winter ice coverage is achieved. Spring melt and break-up begins offshore and in rivers in late May and progresses shoreward. By June or July, open water is present in both nearshore and offshore areas.

Newly formed ice is generally weak and subject to movement by wind and waves, often forming pileups and ridges. By late winter, landfast ice approximately 6.5 ft (2 m) thick extends from the shore out to a depth of about 50 ft (15 m). Nearshore waters shallower than 6.5 ft (2 m) usually freeze to the bottom. Seaward of the 6.5 ft (2 m) depth contour, sea ice floats and can be displaced into ridges (NRC 2003a).

At water depths ranging from 50-150 ft (15-45 m), a shear ice zone exists where landfast ice is sheared by mobile pack ice, resulting in a system of pressure ridges and ice buildups. Ice buildup may cause large pieces of ice to gouge the bottom. Seaward of the shear ice zone is the pack ice zone, consisting of first-year ice, multi-year floes, and ice islands. The Bering Sea gyre causes the pack ice to move from east to west at a rate ranging from 1.4 to 4.6 mi (2.2 km to 7.4 km) per day In June, the sea ice begins to retreat, reaching its furthest north point in September. By mid-July, the Beaufort Sea is usually ice-free out to 6 to 60 mi (10 to 100 km) offshore (NRC 2003a).

Figures 2 and 3 contain maps of the Beaufort Sea region to illustrate the location of various ice zones: a nearshore map (Figure 2) showing the approximate depth contours at 6 ft (approximately 2 m) and 50 ft (approximately 15 m) depth and an offshore map (Figure 3) showing the 150 ft (approximately 45 m) depth contour. The 6 ft (approximately 2 m) contour represents the nearshore areas that generally freeze to the bottom. The area from 6 to 50 ft (approximately 2 to 15 m) generally contains floating sea ice. From 50 to 150 ft (approximately 15 to 45 m) is the shear ice zone, which extends approximately 30 miles (50 km) offshore.

Figure 2. Map of Nearshore Beaufort Sea with the approximate depth contours.

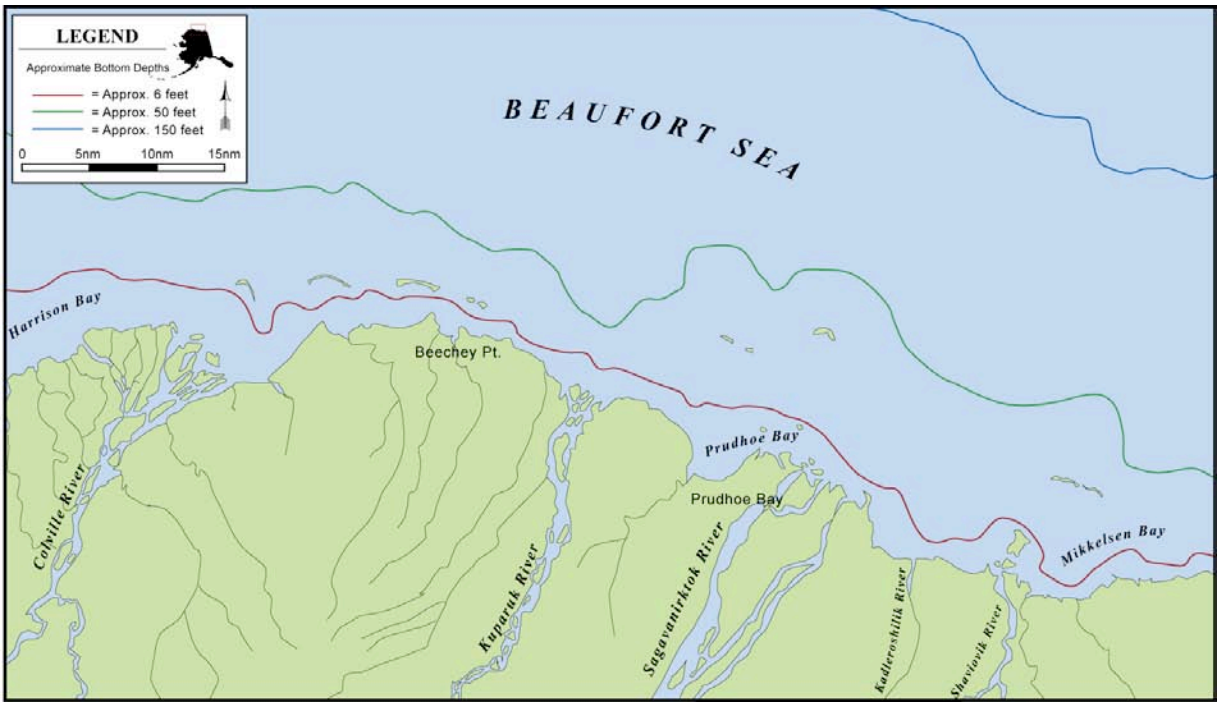
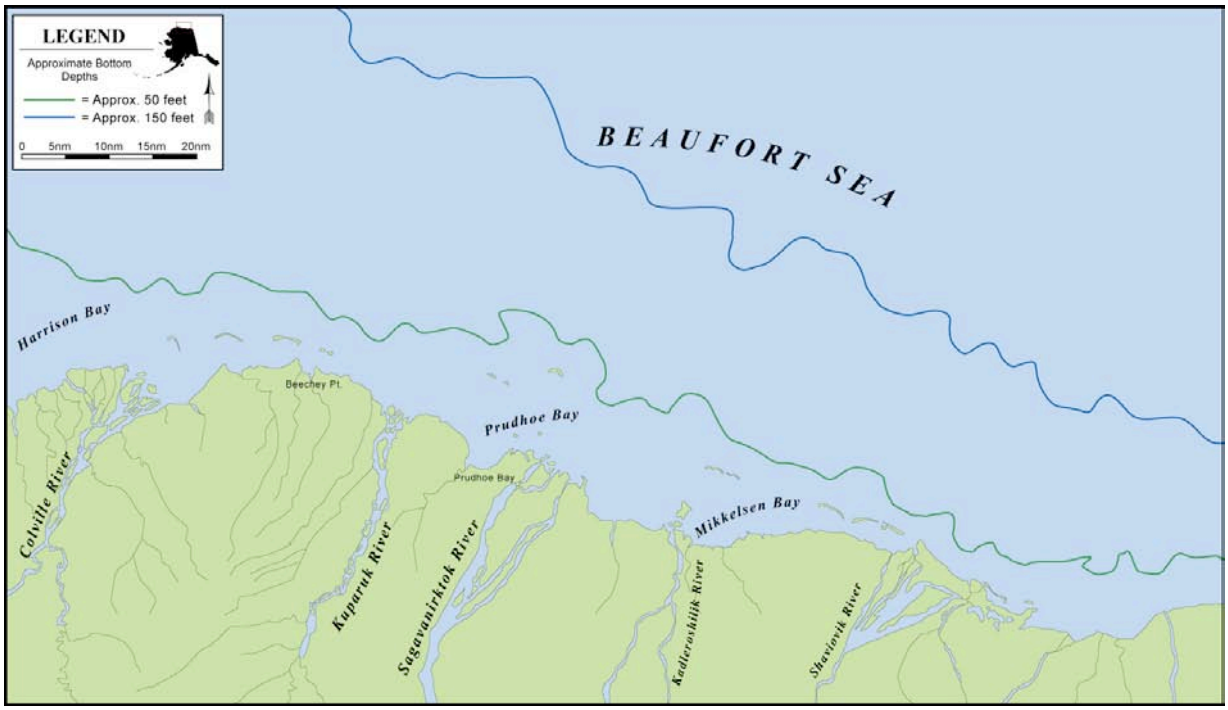


Figure 3. Map of Beaufort Sea with the approximate depth contours.



1.4.2 CONSIDERATIONS FOR MECHANICAL RECOVERY IN BEAUFORT SEA ICE CONDITIONS

The coastline of the Beaufort Sea near Prudhoe Bay is characterized by a coastal wetland and a shallow nearshore area inside a series of barrier islands. Water depths of less than 6 ft extend as far as two miles offshore and water depth of less than 12 ft extend as far as five miles offshore. Because of the extremely shallow nearshore water depths, the deployment and operation of many mechanical recovery technologies may be limited by vessel access to these shallow areas. Sea ice further complicates oil spill response operations, particularly during fall freeze-up and spring break-up.

Shallow nearshore areas will ultimately become part of the landfast ice cover; therefore once the winter ice has formed, spill response in nearshore areas may be accomplished directly from the landfast ice pack. However, during freeze-up and break-up, ice conditions in the nearshore area are more dynamic. Vessels and equipment attempting to clean up an oil spill must be able to operate in the shallow waters and in and among ice of varying concentrations and formations.

Offshore, in pack ice, dynamic ice conditions may exist through the winter. However, water depths will allow for the operation of larger, deeper-draft vessels, which may be more suited to the ice environment.

Because of the variation in water depth and the range of ice conditions possible in nearshore and offshore areas as ice season progresses, spill recovery technologies must be adaptable to a range of conditions. Deployment and operation will be effected both the by the ability for the equipment to function within the range of

ice conditions encountered, and the ability for vessels to deploy and tend the equipment at the appropriate water depth and under the same range of ice conditions.

Freeze-up and break-up ice conditions pose the greatest challenge to responders, as the unstable ice conditions can reduce the likelihood of safely accessing and recovering the spilled oil. The timing and duration of freeze-up and break-up vary from year to year and are influenced by storms and other weather patterns. The length of time required for nearshore areas to progress from initial ice formation to fast ice has been estimated at 26 days. Another 16 days, on average, is required for fast ice to form outside the barrier islands. These estimates represent the worst-case scenario; much faster freeze-up periods occur in many areas of the Beaufort Sea (Oasis and Dickins 2006).

Spring break-up usually begins with overflooding of the ice. As ice conditions degrade, open water areas begin to form and grow. The length of time required to progress from initial overflood to open water varies by region, with overflood generally occurring in May or June. Break-up is usually complete by early to mid August in all nearshore regions (Oasis and Dickins 2006).

In general, the transitional ice period lasts longer during spring break-up than during fall freeze-up. During both transitional ice seasons, response operations may be limited or precluded by the presence, concentration, and movement of broken ice. The 2000 North Slope broken ice response trials in the Beaufort Sea confirmed that the operating limits for a barge-based recovery system were extremely low during freeze-up (0 to 1% ice coverage) and lower than expected during break-up (10% without ice management, 30% with extensive ice management) (Robertson and DeCola 2001).

The Beaufort Sea operating environment presents several unique challenges to vessel operations, which are the basis of most on-water mechanical recovery. Vessel classification schemes typically used to describe oil spill response vessels consider Class 1 and Class 2 vessels, the largest response vessels, to be appropriate for use in ice-infested waters due to their larger, more durable hulls. However, in the Beaufort Sea, such vessels could never operate in the shallow 3-6 foot water depths that characterize much of the nearshore environment. Therefore, smaller vessels are typically used to deploy mechanical recovery equipment in this area.

If the Class 1/Class 2 standard were strictly adhered to on the North Slope, no on-water recovery would be possible in the nearshore area during ice season. However, in reality, ACS vessel operators are generally quite proficient at operating smaller response vessels in ice-infested waters in order to access the nearshore shallows. The determination of which vessels may be safe to operate in and among sea ice is based in a series of complex interactions, including the type and concentration of ice present, the experience of the operator, and the provision for back-up safety plans in the event that a vessel becomes stuck or disabled by the ice.

Because of the unusual combination of conditions in the Beaufort Sea, the question of which response vessels are appropriate is extremely important to the selection and deployment of equipment. Once it has been determined that a vessel can safely operate among sea ice, the next challenge is to find response equipment that is scaled appropriately for the vessel size and power.

1.5 Operating Environment Classifications

For the purpose of this discussion, oil spill equipment will be classified according to the operating environment for which it is suited. The operating environment classification system used in this report follows the system used in the *World Catalog of Oil Spill Response Products – Eighth Edition* (Potter, 2004), which is based on the standards of the American Society of Testing and Materials (ASTM) *Standard Practice for Classifying Water Bodies for Spill Control Systems* (ASTM, 2003). This classification scheme is observed by the State of Alaska in the Spill Tactics for Alaska Responders (STAR) manual (Nuka Research, 2006). Under this classification scheme, oil spill response equipment is rated to perform in one or more operating environments. Table 1 summarizes the classifications scheme for on-water operating environments and indicates which operating environments exist in the Beaufort Sea.

Table 1. Operating Environment Classifications (Potter, 2004 and ASTM, 2003).

Operating Environment	Significant Wave Height	Examples of General Conditions	Existence in Beaufort Sea
Open water	≤ 6 ft.	Moderate waves, frequent white caps	During ice-free season, open water exists outside of barrier islands where wave height exceeds 3 ft. During ice season, open water exists in ice-free areas beyond the shear ice zone (depths > 150 ft.).
Protected water	≤ 3 ft.	Small waves, some white caps	During ice-free season, protected water generally exists landward of the barrier islands.
Calm water	≤ 1 ft.	Small, short non-breaking waves	Not typically encountered in the Beaufort Sea.
Fast water	≤ 1 ft.	Small, short non-breaking waves with currents exceeding 0.8 knots, including rivers	Not typically encountered in the Beaufort Sea.
Broken ice	≤ 1 ft.	Ice coverage exceeds 10%	Broken ice exists in the Beaufort Sea during fall freeze-up and spring break-up periods. Broken ice can be encountered throughout the range of water depths where sea ice forms. Broken ice may be encountered in the shear ice zone (50 to 150 ft depth) and beyond throughout the ice season depending upon other environmental conditions. Broken ice season in nearshore areas is generally quite short (a few weeks in duration), but in deeper waters can take longer. Weather patterns and storms can also impact the timing and duration of broken ice in the Beaufort.
Solid ice	Not applicable	Ice coverage is 100% and is of sufficient strength to support response operations	In mid-winter, solid ice exists in the Beaufort Sea from the shoreline out to approximately 50 ft. of water depth.

2. Assessment of Technology for Mechanical Recovery in Ice-infested Waters

This section reviews the state-of-technology for mechanical recovery of oil spills in ice-infested waters by considering the available technologies on the market today and in the stockpiles of various arctic and sub-arctic nations. Experimental technologies are also described to consider whether emerging technologies may offer significant improvements over existing equipment. The information in this section was compiled through literature review, queries of arctic oil spill response equipment manufacturers, researchers, government agencies in other circumpolar nations, and oil spill response co-operatives in arctic regions. This analysis is biased toward equipment and technologies that have been reported or described in English-language publications. Information about technologies considered to be available in Alaska for use in the Beaufort Sea was compiled by reviewing the Alaska Clean Seas (ACS) Technical Manual and the equipments lists for Beaufort Sea contingency plan (C-plan) holders during the summer of 2006. Information is included regarding experimental technologies and international research and development efforts, where available through published sources or communications with equipment manufacturers and researchers.

2.1 Containment

2.1.1 AVAILABLE TECHNOLOGIES

Containment booms considered in this section include open water boom and protected water boom. Since open water booms have a higher tensile strength and better sea keeping characteristics, they are generally better suited for use in offshore ice conditions than protected water booms, because they stand up better to the strain of deployment in ice. However, open water booms may be too cumbersome to deploy in the shallow nearshore areas of the Beaufort Sea; therefore, a few models of protected-water boom with high fabric tensile strength and tear strength are also considered in terms of their ability to function in nearshore ice-infested waters.

Table 2 summarizes the protected and open water booms described in the *World Catalog of Oil Spill Response Products*, hereafter *World Catalog*, (Potter, 2004) that may be appropriate for use in ice-infested waters based on published reports, manufacturer data, or equipment specifications (e.g., tensile strength or tear strength of fabric).

Appendix B provides an overview of containment boom technologies and tactics, and general considerations for deployment in Beaufort Sea ice conditions.

Table 2. Specifications for Protected and Open water booms that may be appropriate for use in the nearshore and offshore Beaufort Sea during ice season.

Manufacturer	Model	Operating Envt	Boom Type	Height (in)	Total Strength (lb)	Fabric Tensile Strength (lb/in)	Fabric Tear Strength
Allmaritim AS	NOFI 400 EP	protected water	Curtain, internal foam	40	43000	685	72
Allmaritim AS	NOFI 450 S	open water	Curtain, pressure-inflatable	57	51800	740	520
Allmaritim AS	NOFI 600 S	open water	Curtain, pressure-inflatable	69	64000	740	520
Allmaritim AS	NOFI 800 S	open water	Curtain, pressure-inflatable	51	79000	740	520
Allmaritim AS	NOFI 1000 S	open water	Curtain, pressure-inflatable	92	79000	740	520
Aqua-Guard Spill Response, Inc.	AIRFLEX-150S	protected water	Curtain, pressure-inflatable	59.1	67000	1600	unknown
Aqua-Guard Spill Response, Inc.	AIRFLEX-150SC	protected water	Curtain, pressure-inflatable	59.1	67000	1600	unknown
Aqua-Guard Spill Response, Inc.	AIRFLEX-SF	protected water	Curtain, pressure-inflatable	59.1	67000	1600	unknown
Aqua-Guard Spill Response, Inc.	AIRFLEX-SCF	protected water	Curtain, pressure-inflatable	59.1	67000	1430	unknown
Aqua-Guard Spill Response, Inc.	AIRFLEX-100S	protected water	Curtain, pressure-inflatable	39.4	43000	550	unknown
Aqua-Guard Spill Response, Inc.	AIRFLEX-100SC	protected water	Curtain, pressure-inflatable	39.4	42000	500	unknown
Aqua-Guard Spill Response, Inc.	AIRFLEX-SF	protected water	Curtain, pressure-inflatable	39.4	34600	500	unknown
Aqua-Guard Spill Response, Inc.	AIRFLEX-SCF	protected water	Curtain, pressure-inflatable	39.4	32000	500	unknown
Lamor	HDB 1000	protected water	Curtain, pressure-inflatable	39	31000	500	unknown
Lamor	HDB 1300	protected water	Curtain, pressure-inflatable	51	55400	722	unknown
Lamor	HDB 1500	open water	Curtain, pressure-inflatable	59	unknown	1600	unknown
Lamor	HDB 2000	open water	Curtain, pressure-inflatable	78	unknown	1600	unknown
Lamor	HDB 2200	open water	Curtain, pressure-inflatable	87	unknown	1600	unknown
Nordan	OCEAN BOOM	open water	Curtain, inflatable	unknown	unknown	unknown	unknown
Norlense AS*	NO-800-R OCEAN BOOM	open water	curtain, self-inflating	31	unknown	unknown	
Norlense AS*	NO-1000-R OCEAN BOOM	open water	curtain, self-inflating	39	unknown	unknown	unknown
Norlense AS*	NO-1200-R OCEAN BOOM	open water	curtain, self-inflating	47	unknown	unknown	unknown

Manufacturer	Model	Operating Envt	Boom Type	Height (in)	Total Strength (lb)	Fabric Tensile Strength (lb/in)	Fabric Tear Strength
Norlense AS*	NO-1370-R OCEAN BOOM	open water	curtain, self-inflating	54	unknown	unknown	unknown
Ro-Clean Desmi	TROILBOOM GP 1100	protected water	Fence	44	49800	722	158
Ro-Clean Desmi	RO-BOOM 1300	protected water	Curtain, pressure-inflatable	43	43000	720	100
Ro-Clean Desmi	RO-BOOM 1500	open water	Curtain, pressure-inflatable	59	45000	1430	190
Ro-Clean Desmi	RO-BOOM 1800	open water	Curtain, pressure-inflatable	71	45000	1430	190
Ro-Clean Desmi	RO-BOOM 2000	open water	Curtain, pressure-inflatable	79	45000	1430	190
Ro-Clean Desmi	RO-BOOM 1500 HD	open water	Curtain, pressure-inflatable	59	45000	2300	190
Ro-Clean Desmi	RO-BOOM 2000 HD	open water	Curtain, pressure-inflatable	79	45000	2300	190
Ro-Clean Desmi	RO-BOOM 3500 HD	open water	Curtain, pressure-inflatable	137	90000	2700	unknown
Vikoma International Limited	Terminal Boom	protected water	Curtain, pressure-inflatable	43	43000	720	88

2.1.1.1 Open Water Boom

The majority of the open water boom stockpiled for use offshore in the Alaska Beaufort Sea is Ro-Boom. ACS stocks the 1500 and 2000 series, which correspond to the height in mm at the connector. During a series of broken ice trials conducted in the Beaufort Sea during 2000, Ro-Boom was observed to function during freeze-up in low ice concentrations (<10%) and during break-up in low to moderate ice concentrations (up to 30% total coverage, with ice management). Ro-Boom is available in an HD series, which is slightly more durable and comes in two larger sizes not currently stockpiled in Alaska: 2000 and 3500. The HD series is reported to be slightly more effective than regular Ro-Boom in ice. Figure 4 shows Ro-boom.

Figure 4. Ro-Clean Desmi Ro-Boom.

Alaska North Slope stockpiles include limited quantities of Lamor heavy-duty boom in the 1500 series. Larger sizes of this open water boom are also available, ranging from 1600 to 2200. Lamor HDB is shown in Figure 5. Nordan inflatable ocean boom is also available in North Slope inventories in the 600 and 350 models. Manufacturer data could not be located for this boom, nor was it listed in the World Catalog.

Figure 5. Lamor HDB.

NOFI rapid deployment ocean boom (EP series) is available in limited quantities through ACS. The 250 and 350 series (protected water) are stockpiled in Alaska; the 400 and 500 series, which are larger and heavier and rated for open water use, are not.

Norlense NO-800-R is an offshore boom that has been used and tested extensively in sea ice in Norway. More than 35 of these systems are in daily use on the Norwegian continental shelf, where they are regularly used to boom gas condensate vessels loading in ice-infested ports (Figure 6). The boom has reportedly been deployed in temperatures as low as -28°C. These booms are self-inflating, with a single point of inflation. The boom has a hose back-up system that runs the length of the boom and can be used to supply hot air, warm water, or other chemical substances to keep the boom ice and snow-free during operations. The hose back-up remains underwater when not in use to avoid freezing. The Norlense NO-R series of boom is not included in the 2004-2005 World Catalog, therefore comparative data was not available. While the Norlense boom seems well suited to preventative deployment around loading tankers in cold and ice, the manufacturer data does not indicate whether it is appropriate for live deployment configurations. Since this boom was designed for use in ice conditions, it may be worth testing in the Beaufort Sea to determine whether it is adaptable to those conditions (both open water and protected water models).

Figure 6. Norlense NO-800-R deployed around gas condensate tanker during loading operations in Kirkenes, Norway. (Norlense 2006)

2.1.1.2 Protected Water Boom

Most of the booms designed for and tested in ice-infested waters are larger, more durable booms rated for open water use. However, due to the extremely shallow and protected nature of the nearshore Beaufort Sea (particularly landward of the barrier islands), protected water boom may be more appropriate for deployment from the vessels capable of operating in the shallows. Several protected water booms seem appropriate for use in limited ice conditions, based on published data regarding the fabric tensile strength and overall strength of the boom. These include: the Airflex series produced by Aqua-Guard Spill Response, Inc.; some booms from the NOFI EP series (i.e., the 400-EP but not the smaller 250-EP and 350-EP); smaller booms in the Lamor HDB series (i.e., the 1000 and 1300); the Ro-Clean/Desmi Troilboom; smaller Ro-Booms (i.e., the 1300); and the Vikoma International Limited Terminal Boom. Some of these booms – the NOFI EP series, the Troilboom, and the Ro-Boom – have been used or tested to some extent in ice conditions and indicate at least some success. Others have not specifically been tested in ice but might be suited to the Beaufort Sea nearshore environment.

With the exception of the NOFI EP series, the ACS inventory does not appear to include many of the protected water booms considered here. This may be because protected water booms are not traditionally marketed or considered for use in ice-infested waters.

2.1.2 EXPERIMENTAL TECHNOLOGIES

There are no novel technologies for oil booms described in the literature. A Joint Industry Program (JIP) focused on improving oil spill response technologies in arctic and ice-infested waters has identified winterization of existing boom as a research priority (Singsaas 2006).

2.1.3 ASSESSMENT OF OPEN AND PROTECTED WATER CONTAINMENT BOOM FOR THE BEAUFORT SEA

Table 3 considers several models of protected and open water boom that are readily available on the market and currently stockpiled in Alaska and/or other arctic regions in the context of most the BAT requirements at 18 AAC 75.445(k)(3). (Note that cost is not considered in this analysis).

The BAT analysis reflects available information compiled from a variety of sources. One frustration in compiling this data is that the World Catalog does not provide any data regarding the use of specific equipment in ice conditions. While the ASTM operating environment classifications include broken ice, only the categories of open water, protected water, and calm water are used to classify booms in the Catalog.

Table 3. Technology Assessment for use of selected protected and open water booms in the nearshore and offshore Beaufort Sea during ice season.

Manufacturer	Models	Specifications	Availability	Transferability to Alaska North Slope (18 AAC 75.445(k)(3)(B))	Effectiveness in ice-infested waters (18 AAC 75.445(k)(3)(C))	Operating Environments	Feasibility of Beaufort Sea Deployment (18 AAC 75.445(k)(3)(G))	Other considerations
Allmaratim	NOFI rapid deployment boom EP series	Range in size from 250mm to 500 mm freeboard	Available on market; ACS has moderate quantity of 250EP; limited quantity of 350EP; no other models in stock	Already in use	Not specifically designed for use in ice, but favored for use offshore in cold climates. Lower fabric strength than Ro-boom.	open water (450 and above); protected water (250 to 400)	Deployment has already been demonstrated. Could be used in discontinuous, sparse ice coverage only.	Age and maintenance of boom may affect functionality.
Aquaguard	Airflex Series	Range in size from approx. 40 in to approx. 60 in.; high overall and fabric tensile strength	Available on market; not currently stockpiled on North Slope	Other boom of similar sizes in use on North Slope. Should be transferable.	No data available regarding use in ice.	protected water	No data available regarding use in ice. Size makes it suitable for nearshore deployment.	
Lamor	Heavy-duty boom (HDB) 1000 to 2200 series	available models range from 1000 to 2200 (corresponding to height in mm at connector). Weight ranges from less than 10 lb/ft to over 17 lb/ft. Fabric tensile strength = 1,600 lb/in.	Available on market; ACS limited quantity of 1500 and 1300	Already in use	Works well in cold temperatures - rated to -40°C; suitable for low ice concentrations only. May work for limited deployments during freeze-up or break-up. Even at low ice concentrations, possible for boom to tear from ice contact. More test data needed.	open water (1500 and above); protected water (900 through 1300)	Deployment has already been demonstrated in Beaufort trials. Chance of fabric tearing from ice impacts. 50% higher tensil strength than Ro-Boom.	Age and maintenance of boom may affect functionality.
Nordan	Inflatable ocean boom (350 and 600)	manufacturer data could not be located; not listed in World Oil Catalog	Available on market; ACS has limited quantity	Already in use	Not specifically designed for use in ice, but favored for use offshore in cold climates. Considered to be comparable to Ro-boom in durability and suitability for use in ice (no test data available).	open water	Deployment has already been demonstrated. Feasible in low to moderate ice concentrations; not suited for continuous, growing ice cover.	Age and maintenance of boom may affect functionality.
Norlense AS	offshore booms (NO-800-R through NO-1370-R)	self-inflatable offshore booms; range in size from 800 mm to 1370 mm height	Available on market. Not currently stockpiled in Alaska	Currently in use in Norway in ice conditions at very cold temperatures. Manufacturer data indicates primarily used for preventative booming. Might require further testing to determine use in spill response.	Used frequently in Norway for preventative booming of tankers in high ice concentrations; tested & used in ice conditions		Deployed in similar ice conditions in Norway. Should be considered under North Slope conditions	Boom has self-heating mechanism (hose) that may reduce icing/snow load on boom. Boom is not included in 2004-2005 world oil catalog
Ro-Clean/ Desmi	Inflatable Ro-boom 1500 to 2000 Series	available models range from 1500 to 2000 mm in height at connector. Weight ranges from 7 lb./ft for 1500 to 8.7 lb/ft for 2000. Fabric tensile strength = 1,430 lb/in. Tear strength = 190 lb.	Available on market; ACS has significant quantity of 1500 & 2000 series.	Already in use	High cold crack/flexibility rating. Generally considered suitable for use in ice-infested waters at low to moderate concentrations. Freeze-up conditions over 10% ice coverage problematic. Should work in spring ice conditions up to 30%	open water	Deployment has already been demonstrated. Feasible in low to moderate ice concentrations; not suited for continuous, growing ice cover.	Age and maintenance of boom may affect functionality.
Ro-Clean/ Desmi	Inflatable Ro-Boom HD 1500 to 3500 Series	Models range from 1500 to 3500 mm in height at connector. Weight ranges from 9.7 lb./ft for 1500 to 16.9 lb/ft for 3500. Fabric tensile strength = 2,300 lb/in. Up to 2000 series and 2,700 lb/in for 3500. Tear strength = 190 lb up to 2000; unavailable for 3500.	Available on market; HD series not in stock at ACS.	Other Ro-boom models already in use on North Slope.	Manufacturers report slightly better performance in ice than regular Ro-Boom.	open water	May be deployed in similar or slightly higher ice conditions than regular Ro-boom. Higher weight and larger size of 3500 series may require additional deployment capability.	

2.2 Recovery

2.2.1 AVAILABLE TECHNOLOGIES

Several types of skimmers, using a range of technologies, are marketed for use in arctic regions and ice-infested waters. These are summarized in Table 4.

Table 4. Specifications for protected and open water skimmers that may be appropriate for use in the nearshore and offshore Beaufort Sea during ice season.

Manufacturer	Model	Operating Envt	Operating Mode	Skimmer Type	Weight (lbs)	Comments
Frank Mohn Flatoy A/S	Transrec 100	open water	advancing	weir/disc/belt/ HiVisc/HiWax	14,000	
Frank Mohn Flatoy A/S	Transrec 125	open water	advancing	weir/disc/belt/ HiVisc/HiWax	16,000	
Frank Mohn Flatoy A/S	Transrec 150	open water	advancing	weir/disc/belt/ HiVisc/HiWax	28,000	150 model is highest listed in world catalog; ACS inventory lists 250
Lamor	Arctic Skimmer (LAS) 125	protected water	stationary	brush wheel	1700	
Lamor	Side collector LSC-2-C	protected water	advancing	chain brush	800	
Lamor	Minimax 12 W	protected water	stationary/ advancing	brush wheel	62	
Lamor	Minimax 20 W	protected water	advancing/ stationary	brush wheel	180 - 240	
Lamor	Minimax 30	protected water	advancing	brush wheel	485-567	
Lamor	LRB W	protected water	stationary	brush wheel	2,000	
Lamor	Side Collector LSC-3 C	open water	advancing	chain brush	1,300	
Lamor	Side Collector LSC-3 W	open water	advancing	brush wheel	937	
Ro-Clean Desmi	SEAMOP 3040	protected water	stationary	suspended rope mop	247	
Ro-Clean Desmi	SEAMOP 5060	protected water	stationary	suspended rope mop	355	
Ro-Clean Desmi	DBD 15	protected water	stationary/ advancing	disc/brush drum	190	
Ro-Clean Desmi	DBD 22	protected water	stationary/ advancing	disc/brush drum	220	
Ro-Clean Desmi	DBD 40	open water	stationary	disc/brush drum	330	
Ro-Clean Desmi	DBD 60	open water	stationary	disc/brush drum	330	
Ro-Clean Desmi	weir 250	open water	stationary/ advancing	weir	375	no longer on market, although similar models available
Ro-Clean Desmi	SEAMOP 4090	open water	stationary	suspended rope mop	1,300	
Ro-Clean Desmi	SEAMOP 8090	open water	stationary	suspended rope mop	2,000	

The ACS inventory contains a limited number of skimmers suited for use in ice-infested waters (approximately 13 units based on ACS inventory dated May 2006). These include oleophilic (brush and rope mop skimmers) and weir skimmers. The LSC-3 side collector (Figure 7) and the Lori brush pack skimmer are probably the best suited to offshore oil recovery operations in ice. They are rated to work in widely dispersed, newly forming ice but not in a continuous growing ice cover. Freeze-up conditions will significantly limit encounter rates.

Figure 7. Lamor side collector (LSC). (Lamor 2006)

There are two rope mop skimmers (Figure 8) in the ACS inventory, which can recover oil until ice becomes a continuous cover, but is reported to have problems at sub-freezing temperatures because the rope mop may freeze and ice may build up at the wringers (BPXA 2003). Entanglement of the mop with ice pieces is also possible, and rope mop skimmers tend to work best in concentrated, thick oil slicks (Counterspill, 1992).

Cook Inlet Spill Prevention and Response Inc (CISPRI) has been actively experimenting with their rope mop system to determine the best procedures to minimize interference by ice crystals freezing in the rope. Field tests in 2007 led them to believe that using new ropes, shortening the rope length, and placing the correct amount of rope in contained oil are important ways to minimize ice formation (CISPRI, 2007). New ropes are less frazzled than used ones and present less matrix for ice crystal growth. Shortening the ropes and only placing the minimum amount of rope in pooled oil will minimize wetting which leads to ice growth.

Rope mop skimmers are still favored for use in ice under certain conditions, because they can be easily deployed from vessels of opportunity in many positions and can be readily positioned in ice (Solsberg and McGrath 1992). Vertically-oriented rope mops like the Foxtail allow for selective positioning since there is no need to actively process ice encountered by the recovery unit, and Foxtail rope mops are the predominant skimmer used in Norway in ice conditions (Brandvik *et al.* 2006).

Figure 8. Foxtail rope mop skimmer. (Nuka 2007)

ACS has three Desmi 250 weir skimmers, which are self-floating weir skimmers with a vertical Archimedes screw head (Figure 9). These skimmers have limited effectiveness in ice-infested waters above very low ice concentrations. The skimmer tends to clog at the screw auger pump and has low encounter rates in ice (BPXA 2003).

Figure 9. Desmi 250 weir skimmer. (Allmaritim 2006)

There are a few other types of skimmers that are marketed for arctic use but not currently stockpiled in Alaska. Bucket skimmers are a variation of a weir or oleophilic brush skimmer that can be used in either mode. A bucket skimmer is mounted on an articulating arm that allows the skimmer head to be quickly moved from one pool of oil to another. Its dual mode allows it to process pools of oil on ice and in the water. The Lamor recovery bucket (LRB) is specifically designed for cleaning pit spills on land, in water, and in ice. The skimmer combines the Lamor brush wheel with an excavator scoop and a screw pump. The skimmer is designed to work among floating debris, including ice. The brush wheel can be hydraulically lifted to allow the bucket to be used to scoop and dump heavy oil sludges and solid materials, and to move large ice chunks at sea. The LRB can be deployed and operated by a small crew, and for on-water spills would be deployed from a vessel crane. Figure 10 shows several photos and diagrams of the LRB, including examples of the LRB skimmer operating in ice. In tests conducted by the Technical Research Center of Finland (VTT), the recovery efficiency in ice-infested waters was about 50%. The LRB has reportedly been used in actual spills with similar good results (Brandvik 2006).

Figure 10. Lamor Recovery Bucket. (Lamor 2006)

The Lamor Arctic Skimmer (LAS 125) was developed specifically for use in ice-infested waters under extreme cold conditions. The skimmer uses static ice deflection pipes and rotating brush wheels for oil separation and collection. The brush wheel discs revolve in the same direction as the flow of the oily water passing through the skimmer, and the revolving brush forces oil under the water surface, where it then migrates upward and adheres to the brushes. Any encountered ice pieces are crushed by the ice-crushing screws inside the hopper and these screws also feed the oil to the built-in Archimedes screw transfer pump. The Arctic Skimmer is deployed from a crane or davit, but can also be fitted with floats if needed. While it is rated for protected water use, it's high weight (1,700 lbs) may make it too large to deploy from nearshore response vessels. Figure 11 shows the Lamor Arctic Skimmer operating in high ice concentrations.

Figure 11. Lamor Arctic Skimmer. (Lamor 2006)

The Lamor Minimax series are light, portable suction skimmers that use a brush wheel system in stationary mode to recover oil in protected water environments. The largest model (Minimax 30) is fitted with a brush conveyor belt rather than a wheel. All models can be adapted to use an Archimedes screw auger pump to manage ice and debris.

Desmi Disc Brush Drum (DBD) skimmers are not specifically marketed as arctic skimmers, but the manufacturer (Desmi Ro-Clean) reports that they have been used very recently for recovery of oil in ice in Greenland (Figure 12). The Desmi DBD is produced in a variety of configurations – single, twin or triple banks of rotating oleophilic discs or brush drums. Independent hydraulic, electric or pneumatic motors drive these discs. Oil is recovered from the water as it adheres to the surface. As the discs or drum brushes are rotated through the skimmer head, oil is collected in the central sump on a continuous basis.

Figure 12. Desmi DBD during use in harbor spill in Tassilaq, Greenland. (Jensen 2006)

2.2.2 EXPERIMENTAL TECHNOLOGIES

A commonly noted problem with oil recovery technologies that work in ice conditions is that they tend to favor small batch recovery. Research and development efforts in arctic skimming continue to focus on technologies or adaptations to increase recovery capacity for oil in ice-infested waters. The JIP recommends further investigation of a skimming concept that combines a weir skimmer with a brush type skimmer on top to promote higher capacity oil collection while deflecting ice from the weir (Singsaas 2006).

A team of researchers at the University of California Santa Barbara (UCSB) has experimented with new skimmer surfaces in an attempt to better understand the adhesive properties of oils and oil emulsions at different weathering degrees toward various surfaces (e.g. steel, polymers, ice, etc.). In a series of full scale wave tank tests at Ohmsett in 2005, a variety of interchangeable oleophilic drums were tested with a range of test oils, environmental conditions, and operational parameters to determine whether any of the novel skimmer surfaces offer improved effectiveness over exiting materials. The drum surfaces were either smooth or grooved and were constructed of aluminum, polyethylene, polypropylene, neoprene, or hypalon (Figure 13). The tests found that the use of a grooved surface could increase recovery up to 200%. This efficiency could be further improved by tailoring the groove dimensions depending upon the type of oil and ambient conditions. The tests also found that the selection of drum materials could improve recovery efficiencies by an additional 20%. This improvement was most pronounced in thin slicks (Broje and Keller 2006).

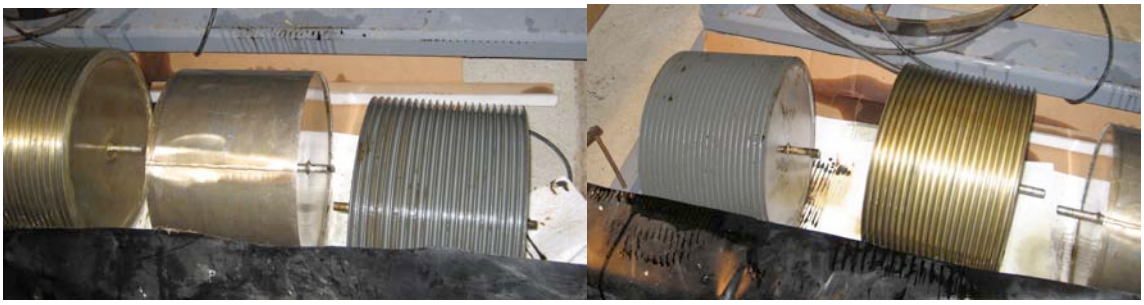
Figure 13. Grooved drums installed into a skimmer frame. U.S. Provisional Patent Application (serial no. 60/673,043) by UCSB. Left - aluminum drum. Right – Neoprene-coated drum with matching scraper. (Broje and Keller 2006)

In March 2007, the UCSB researchers continued these tests at the US Army Corps of Engineers Research and Development Center Cold Regions Research and Engineering Laboratory (CRREL). They conducted a series of full-scale oil spill recovery tests utilizing CRREL's Materials Evaluation Facility to evaluate a variety of oil skimmer designs under different cold water and sea ice conditions. The tests were conducted at CRREL's cold facility, a refrigerated laboratory (ambient temperature 10° F). A small test tank was set up in the facility, as shown in Figure 14.

Figure 14. Small test tank set-up at CRREL cold water research facility. (ADEC Lydia Miner 2007)

The drum skimmer tests compared the efficiencies of different skimmer surfaces and drum speeds to the recovery efficiencies of each under a range of cold water and ice conditions. Figure 15 shows the range of skimmer drum surfaces tested. Three different oils (HydroCal, North Slope Endicott Crude, and diesel) were used. Drum skimmers were modified to use various surface patterns and materials to recover the oil. Water temperature was 30° F for all tests. Tests were conducted either with or without ice present. For the tests conducted in ice, frazil ice ("slush" consistency) was used, with 30% ice in oil by weight.

Figure 15. Range of skimmer drum surfaces tested. (ADEC Lydia Miner 2007)



The grooved skimmers were further modified by adding a "scraper," as shown in Figure 16. The stiff plastic scraper is cut to fit the grooves on each skimmer and was very effective at removing the collected oil from the grooves.

Figure 16. Grooved skimmers. (ADEC Lydia Miner 2007)

During the 2007 CRREL tests, which were observed by ADEC staff and contractors, the grooved drums had higher recovery rates than the smooth ones, in both ice and ice-free conditions. Drum speeds ranged from 10-60 RPM. The presence of the slush ice had little apparent effect on the grooved drum, and the skimmer seemed to process that type and concentration of ice quite effectively. No tests were conducted with larger chunks of ice, so it is not clear what the limit of ice chunk size might be on the skimmer's operations.

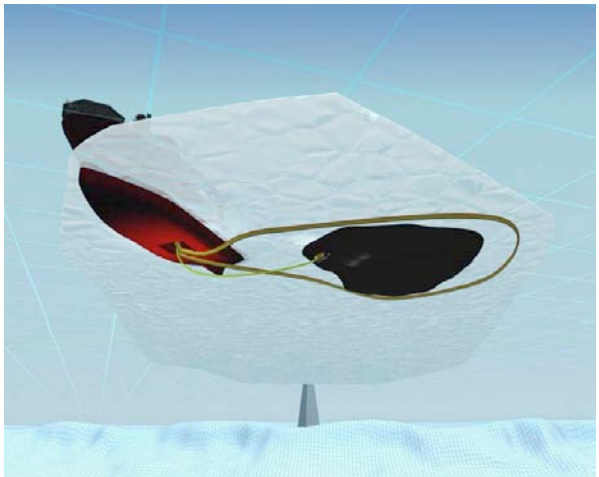
Preliminary results from the researchers estimate the range of recovery rates from 20-40 gal/min for the grooved drums, and 5-15 gal/min for the flat drums. Final results will be published in a report to MMS and OSRI by summer 2007.

Elastec, the manufacturer of the drum skimmers tested at CRREL, indicated that they would be modifying all their oil skimmers to use the grooved surfaces.

The novel skimmer surface design allows for drums to be quickly switched out from the skimmer, so that responders can tailor their skimmer surface based on the type of oil spilled and on-scene conditions. This offers a relatively low-cost option that may expand mechanical recovery capabilities under a range of conditions, including possibly the presence of sea ice. The brush drum skimmer can be easily deployed from a vessel hydraulic arm to recover oil in ice-infested waters.

A new concept for oil recovery in ice proposes the adaptation of a Transrec skimmer system for use under ice through the moon pool of a supply vessel. This technology (Figure 17) is currently in the early stages of proposal and has not been engineered or tested.

Figure 17. Conceptual diagram of under-ice recovery system. (Framo in Brandvik 2006)



2.2.3 ASSESSMENT OF RECOVERY SYSTEMS FOR THE BEAUFORT SEA

Table 5 considers several models of protected and open water recovery systems that are readily available on the market and currently stockpiled in Alaska and/or other arctic regions in the context of most the BAT requirements at 18 AAC 75.445(k)(3). (Note that cost is not considered in this analysis).

The BAT analysis reflects available information compiled from a variety of sources. One frustration in compiling this data is that the World Catalog does not provide any data regarding the use of specific equipment in ice conditions. While the ASTM operating environment classifications include broken ice, only the categories of open water, protected water, and calm water are used to classify skimmers in the Catalog.

Table 5. Technology Assessment for use of selected protected and open water skimming systems in the nearshore and offshore Beaufort Sea during ice season.

Manufacturer	Models	Specifications	**Availability** (18 AAC 75.445(k)(3)(A))	**Transferability to Alaska North Slope** (18 AAC 75.445(k)(3)(B))	**Effectiveness in ice-infested waters** (18 AAC 75.445(k)(3)(C))	Operating environments	**Feasibility of Beaufort Sea Deployment** (18 AAC 75.445(k)(3)(G))	Other considerations
No manufacturer - concept proposed by researchers	Combination weir/brush drum skimmer concept	brush drum skimmer mounted on top of weir skimmer to reduce ice clogging of weir and maximize recovery	conceptual development only; no prototype; not available on market	Technology not developed therefore not transferable	Not tested in ice-infested waters yet	n/a	Technology unavailable therefore not feasible	
Ro-Clean/ Desmi	Desmi 250 weir	screw auger weir	Available as used on market, no longer manufactured, but similar units are available;3 harbor units in ACS inventory, 1 ocean unit	Already in use	Ice likely to either cause skimmer to clog at pump or to limit encounter rate. May be effective at low ice concentrations during break-up or freeze-up. Could be used to remove stationary, contained oil if ice concentrations low.	Open water	May be effective at lowest ice concentrations. This skimmer weighs 375 lbs, making it suitable for vessels capable of operating in shallow water.	Functions better than rope mop skimmers at freezing temperatures
Ro-Clean/ Desmi	DBD disc brush drum	oleophilic disc or brush drum skimmers produced in a variety of configurations - single, twin or triple banks; smaller models can operate in stationary or advancing mode; larger models operate in stationary mode	Available on market; not in Alaska	Used primarily in harbors; need more data regarding applicability to offshore ice conditions	Have been used in ice-infested waters in harbors. No data available regarding specific performance in freeze-up or break-up.	DBD-15 & DBD-22 rated for protected water; DBD-40 & DBD-60 rated for open water	Open water model weighs 330 lbs. It may be possible to fit this skimmer to a vessel capable of shallow water operations. Protected water models weigh 190 and 200 lbs and have been used in harbors.	Manufacturer provided information on use in harbor spills; offshore application unproven.
Foxden	V.A.B. 2-9 rope mop	oleophilic rope mop skimmer	Available as used on market, no longer manufactured;1 skimmer in ACS inventory	Already in use	Can operate in relatively high ice concentrations when deployed into ice leads or broken ice fields. Icing of mop can cause problems at freezing temperatures.	Open water	The skimmer head must be suspended from a boom or crane and weights 1,929 lbs, This skimmer is not suitable for most shallow water vessels. Can be highly effective for contained, concentrated batches of oil. Does not require ice processing therefore can operate in high ice concentrations	Deployed from cranes. Rope mop skimmers are better suited to batch recovery operations than to large-scale skimming.
H.Henriksen	Foxtail rope mop	oleophilic rope mop skimmer	Available as used on market, no longer manufactured; 1 unit in ACS inventory	Already in use	Can operate in relatively high ice concentrations when deployed into ice leads or broken ice fields. Icing of mop can cause problems at freezing temperatures.		Can be highly effective for contained, concentrated batches of oil. Does not require ice processing therefore can operate in high ice concentrations	Deployed from cranes. Rope mop skimmers are better suited to batch recovery operations than to large-scale skimming.
Lamor	Arctic skimmer LAS 125	oleophilic brush cleaner with rotating brush wheel discs; operates in stationary mode	Available on market; not in Alaska	New skimmer; additional test data needed to evaluate transferability to N. Slope conditions	Designed for use in extreme cold and ice-infested waters. No data available regarding specific performance in freeze-up or break-up.	protected water	This skimmer weighs 1,700 lbs. It may be possible to deploy this skimmer from a vessel suitable for shallow water.	Normally deployed by crane or davit but can be equipped with floats.

Manufacturer	Models	Specifications	**Availability** (18 AAC 75.445(k)(3)(A))	**Transferability to Alaska North Slope** (18 AAC 75.445(k)(3)(B))	**Effectiveness in ice-infested waters** (18 AAC 75.445(k)(3)(C))	Operating environments	**Feasibility of Beaufort Sea Deployment** (18 AAC 75.445(k)(3)(G))	Other considerations
Lamor	Oil Recovery Bucket LRB	oleophilic brush wheel skimmer with excavator bucket; operates in stationary mode.	Available on market; not in Alaska	Used with high success in other arctic nations; should transfer well to N. Slope	Designed for pit cleanup in ice and debris; excavatator can be used to move large ice chunks; marketed and tested for use in ice. Can be highly effective for batch recovery of contained oil in moderate ice conditions. No data available regarding specific performance in freeze-up or break-up.	protected water	This skimmer is rated for protected water and weighs 2,000 lbs. The skimmer must be deployed from a knuckle crane or excavator. It may be difficult to deploy this system in a shallow water environment.	Deployed from crane. Better suited to small-batch (pit) cleanup than to large-scale recovery. Stationary skimmer.
Lamor	Lori brush pack HK3/2.8	oleophilic brush skimmer	Available on market; 4 units in ACS inventory	Already in use	Can operate in widely dispersed ice (<10%) but not in continuous ice cover. Icing and slush collection may cause problems, as with LSC-3.	protected water	This skimmer is rated for protected water and light enough to be deployed on a vessel capable of operating in shallow nearshore areas.	Sub-freezing temperaturs can cause brushes and combs to ice, while small ice pieces can block inlets and hoses.
Lamor	LSC-2 side collector	oleophilic chain brush skimmer; operates in advancing mode	Available on market		Manufacturer indicates same debris-handling capability as LSC-3	protected water	This smaller version of the LSC weighs 570 lbs and requires an external power pack. It may be feasible to use on some small vessels.	
Lamor	LSC-3 side collector	oleophilic chain brush (LSC-3C) or brush wheel (LSC-3W) skimmer; operates in advancing mode from outrigger; sweeping boom part of configuration	Available on market; 3 units in ACS inventory	Already in use	Can operate in widely dispersed ice (<10%) but not in continuous ice cover. Icing and slush collection may cause problems. Most freeze-up conditions will render ineffective. May work better during break-up.	Open water	The weight of this skimmer (1,300 lbs or 937 lbs depending on model) and the requirement that the skimmer have an external power pack, may preclude its use on small vessel capable of working in shallow water enviroments.	Sub-freezing temperaturs can cause brushes and combs to ice, while small ice pieces can block inlets and hoses.
Ro-Clean/ Desmi	SEAMOP	suspended rope mop skimmers, operate in stationary mode	Available on market			3040 and 5060 are protected water models; 4090 and 8090 are open water models		Rope mop skimmers are better suited to batch recovery operations than to large-scale skimming.
Frank Mohn Flatoy A/S	Transrec weir skimmers (100 through 250)	self-floating weir skimmer with Archimedes screw auger pump	Available on market; 1 unit (Transrec 250) in ACS inventory	Already in use	Ice likely to either cause skimmer to clog at pump or to limit encounter rate. May be effective at lowest ice concentrations.	Open water	This skimmer is rated for the open water environement and weights 14,000 to 28,000 lbs., making it much too large for vessels that can operate in shallow water environments.	Still unproven at freezing temperatures. Note that world catalog describes 100, 125 & 150 models. ACS inventory lists 250 model.
Elastec	UCSB novel skimming surfaces	interchangeable oleophilic brush drums with grooved or smooth surfaces and various skimmer materials to optimize recovery rates	Available on market.		Tests in 30% slush ice show that recovery capacity is not significantly impeded by those ice conditions.	would depend on size/scale of brush drum	Skimmer size can be varied for various operating environments. Smaller skimmers are light and transportable. Highly versatile.	

2.3 Ice Processing

2.3.1 AVAILABLE TECHNOLOGIES

Ice processing or oil/ice separator technologies on the market today are fairly limited, although there has been and continues to be considerable research in this area. The following existing technologies are considered in this report (none are currently stockpiled in Alaska):

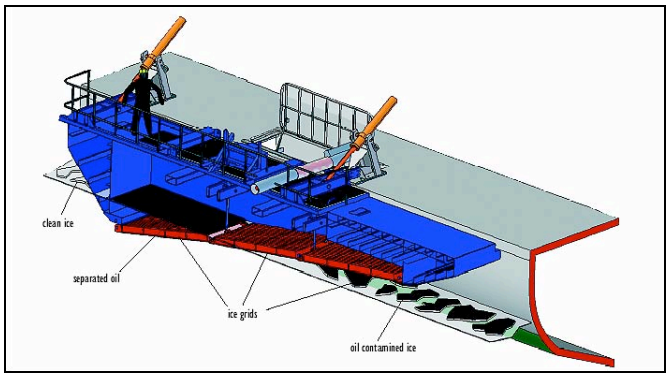
- Lamor Oil-Ice Separator (LOIS)
- Lamor-Lori Ice Cleaner

The Lamor Oil Ice Separator (LOIS) is fairly new to the market and reflects the outcome of considerable research and development efforts by researchers in Finland. The LOIS is an advancing skimming system with a built-in ice processing unit that may be attached to the side of a response vessel (Figure 18). The LOIS is installed on the side of a dedicated response vessel capable of operating in ice conditions. An oscillating ice grid on the forward side of the LOIS separates ice chunks and washes the oil from ice chunks as they move along the grid (Figure 19). The LOIS is sealed tightly against the hull of the response vessel on the lower and aft edges so that as the vessel advances, oil and crushed ice pieces are pushed against the ice grid and forced deeper into the water as they proceed aft. Advancing speed is recommended at 1 to 3 knots depending on ice conditions; however, response experts familiar with this system have noted that the optimal advancing speed is considerably lower, with a maximum rate of 0.7 kts, to allow the oil sufficient time to surface.

Separated oil is concentrated for recovery using a skimmer. Small ice pieces that pass through the grid flow with the oil into the recovery channel, where they are recovered by the brush conveyor. If the volume of small ice pieces is high, a screw conveyor at the top end of the brush conveyor is used to remove most of the material so it can be cleaned and discarded.

Figure 18. LOIS unit. (Lamor 2006)

Figure 19. Schematic of LOIS unit. (Lamor 2006)

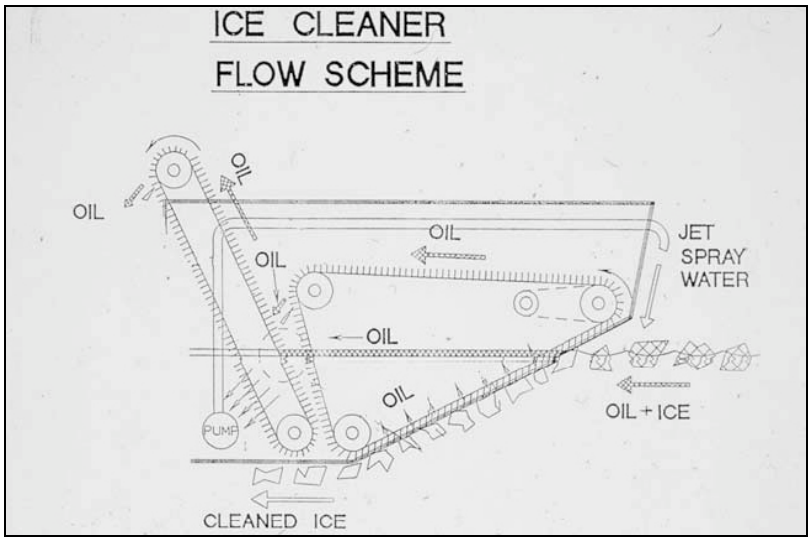


The technology has been developed primarily for vessels with built-in oil recovery systems (Figure 20) but can also be delivered with a Lamor brush skimmer installed. The latter configuration could be mounted on any ice class vessel or barge, although the LOIS, which weighs 66,000 lbs, must be designed according to the specifications of vessel hull. The LOIS can be raised above the ice line for transit to and from the response scene. The system is in use on one vessel in Finland, with plans to develop two others. It is available on the market, although the units appear to be custom-built and might therefore require some lag time before one could be acquired and deployed in Alaska.

Figure 20. Oil recovery system. (Lamor 2006)

The Lamor-Lori Ice Cleaner (LIC) is an older concept dating back to the 1980s. The Ice Cleaner was developed by two Finnish equipment manufacturers to improve mechanical recovery in ice conditions. The LIC is a removable unit weighing 56,000 lbs that is installed on the bow section of an ice breaker or ice-capable work boat. It consists of two sets of brushes and water-spraying nozzles to separate oil from ice pieces. The unit works in two stages: the first stage cleans the ice and the second stage separates the oil from ice and collects the oil for recovery (Figure 21). The unit has a displacement of 25 tons and therefore requires a substantial vessel for mounting and deployment. The recommended vessel size to couple correctly with the unit is between 65 and 130 ft long and 16 to 32 ft wide.

Figure 21. LIC schematic. (Lamor 2006)



A demonstration of the LIC was conducted in January 1991 in Finland, and reported on by a representative of ACS (Bowen 1991). The report notes that the large size and weight of the unit made transport somewhat challenging. The unit must be transported on the deck of the vessel and then deployed with a crane. The unit, supported by an ice breaker, was observed to maneuver well in areas of relatively high ice concentration. However, the skimmer recovery was reported to be more problematic. The first stage brushes tended to freeze upon removal from the water, requiring additional effort to remove the ice from them before redeployment. The water wash system had the unintended effect of herding oil away from the front of the LIC, thereby reducing the encounter rate. This was attributed by some observers to the angle of the water spray. Smaller pieces of ice were transported by the second stage brushes to the collection area where they eventually piled up, further reducing the volume of recovered oil. While several problems were noted with the recovery efficiency, many of these were attributed to the test design rather than to defects in the LIC design. The ACS observer recommended additional testing of the unit with more viscous oils and noted that the technology was promising for spill response in ice-infested waters (Bowen 1991).

A second set of trials was held in March of 1991, addressing many of the test design concerns raised during the first trial. A news release from the manufacturer indicates that during these tests, which used heavy fuel oil, the LIC recovered approximately 50% of the oil. Improvements to the unit prior to this test included a reduction in the speed of the second-stage brush system to improve oil-water separation, and the use of a support vessel with a different propulsion system that resulted in less "pulverizing" of the ice pieces, thereby reducing the smaller pieces of ice that clogged the collection area in previous tests (Latour 1991).

Despite the enthusiastic promotion of the LIC by the manufacturers and the fact that it was regarded as a "promising" technology by an ACS response expert, this

technology does not appear to have been widely marketed beyond the initial unit which is still in use in Finland (Figure 22).

Both the LOIS and the LIC are designed to process smaller rubble-sized ice pieces. They generally cannot handle the much larger ice pieces commonly encountered in the Beaufort Sea during break-up.

Figure 22. LIC unit during 1991 trials. (Lamor 2006)

2.3.2 EXPERIMENTAL TECHNOLOGIES

Several ice processing or oil/ice separator technologies exist in the experimental stage, which for the purpose of this discussion means that they have been developed and tested but are not currently offered through an equipment vendor.

2.3.2.1 MORICE

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

The MORICE project focused on a spill response in ice up to 70% coverage, with mild dynamic conditions and formation of brash and slush ice. The equipment was tested for oils with a range of viscosities. The major challenge was to develop equipment that could recover oil from within ice fields, and also develop ice cleaning methods. The basic concept involved a combination of recovering oil

from within the ice using two different recovery systems, separating ice from oil, and deflecting large pieces of ice to allow the unit to function. The component parts were developed separately and then combined into a single vessel-mounted unit (Jensen and Mullin 2003).

The main component parts of MORICE include: a lifting grated belt that is used to deflect ice away from the recovery unit and process the ice (Figure 23); a Lori brush drum skimmer unit that was adapted with a screw auger to move ice to the rear of the unit (Figure 24); and a MORICE brush-drum recovery unit developed specifically for the project (Figure 25). These component parts were the result of significant trial-and-error and constant re-engineering to meet the demands of ice conditions.

Figure 23. MORICE lifting grading belt. (Jensen and Mullin 2003)

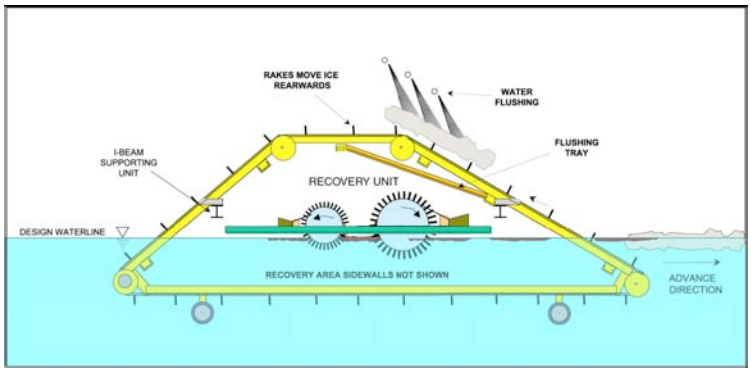
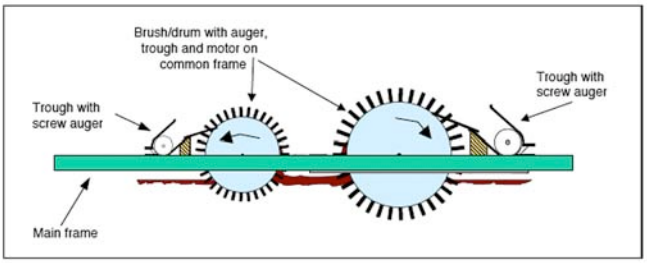


Figure 24. Lori brush drum unit adapted for MORICE. (Jensen and Mullin 2003)

Figure 25. MORICE brush drum skimmer. (Jensen and Mullin 2003)



The MORICE unit itself has not been brought to market, although it is at the stage where it is ready for industrialization. A larger scale unit than the one tested during MORICE would likely be needed for offshore response (Brandvik 2006).

2.3.2.2 Finnish vibrating unit

Researchers in Finland have developed oil spill response devices for ice-infested waters that may be attached to the bow of a vessel and include a combination of ice-processing belts and skimming systems. One configuration uses a vibrating unit to create a flow field under the ice and channel oil toward the skimmer while diverting most ice pieces. The vibrating unit has been improved over time through a series of laboratory and field tests that began in 1997, with successive changes amounting to a reduction in the amount of oil that entered the recovery unit (Rytkonen *et al.* 2003). Earlier tests experimented with a perforated conveyor belt that moves the ice under the vessel while allowing water and oil to flow toward the skimmer unit (Rytkonen *et al.* 2000). Figure 26 shows a prototype during field testing.

Figure 26. Vibrating unit attached to the side of a vessel. (Brandvik 2006)

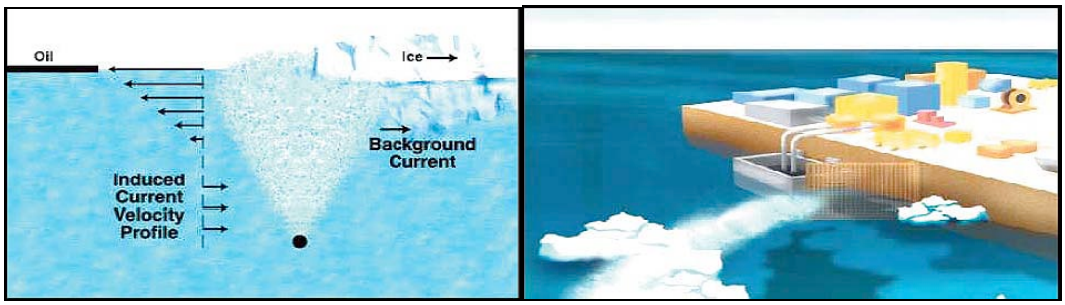
Continued testing and development of this concept has been identified as a priority for the JIP (Singsaas 2006).

2.3.2.3 Pneumatic air curtains

Another concept that has been tested recently is the use of air curtains to separate oil from ice pieces. The use of pneumatic air plumes to remove oil trapped under ice was first tested in Finland in 1993. In 2002, new experiments were conducted where air plumes were released from different water depths (Brandvik 2006, Rytkonen *et al.* 2003).

More recently, researchers at ExxonMobil have tested pneumatic diversion booms for use in ice-infested waters. Figure 27 shows conceptual sketches of these booms, which would function similarly to other oil diversion devices by using water velocity to direct oil in one direction, toward recovery devices, and ice in another (DICKINS, 2004). Additional research and development efforts are needed before the technology can be considered market-ready (Narita *et al.* 2001).

Figure 27. Pneumatic diversion boom concept. (ExxonMobil 2003 in DICKINS, 2004)



2.3.3 ASSESSMENT OF ICE PROCESSING SYSTEMS FOR THE BEAUFORT SEA

Table 6 considers the ice processing systems described above in the context of most the BAT requirements at 18 AAC 75.445(k)(3). (Note that cost is not considered in this analysis).

Since there are only two ice processing systems currently market-available and both require rather large vessels to deploy them, there may be no BAT on the market today for ice processing in the Beaufort Sea. However, existing and experimental technologies might be adaptable to Beaufort Sea operating conditions.

Table 6. Technology Assessment for use of selected ice processing systems in the nearshore and offshore Beaufort Sea during ice season.

Manufacturer	Model	Specifications	Availability (18 AAC 75.445(k)(3)(A))	Transferability to Alaska North Slope (18 AAC 75.445(k)(3)(B))	Effectiveness in ice-infested waters (18 AAC 75.445(k)(3)(C))	Operating environments	Feasibility of Beaufort Sea Deployment (18 AAC 75.445(k)(3)(G))	Other considerations
Lamor	LOIS Oil/Ice Separator	advancing skimming system with a built-in ice processing unit that may be attached to the side of a response vessel	Available on marked; in use in Finland	Technology could be fitted to response vessels in Beaufort Sea - unit must be designed for specific vessel	Designed to function in ice-infested waters. Should function in break-up conditions. Would require additional testing to identify limits in Beaufort Sea freeze-up.	Protected water	Requires identification of dedicated vessel to mount unit on. Should be tested under North Slope conditions.	
Lamor	LIC - Lori Ice Cleaner	removable chain brush unit that is installed on the bow section of an ice breaker or ice-capable work boat; operates in advancing mode	One unit in use in Finland; available on market but must be built	Requires rather large, deep-draught vessel; may not be transferable to shallow areas of Beaufort Sea	Reportedly effective in ice-infested waters. Should function in break-up conditions. Would require additional testing to identify limits in Beaufort Sea freeze-up.	Protected water	Requires consideration of whether unit is too large/heavy for Beaufort Sea vessels.	Technology has been available for 15 years but has not been purchased for use beyond original test unit
N/a	MORICE	ice processing and recovery equipment mounted onto a response platform	Small (harbor-sized) prototype model developed and tested in wave tank and field; No units commercially available	Technology not commercially available but in fairly mature development; could be transferred to North Slope if brought to market	Scale model tested in ice-infested waters in Beaufort Sea and reported to function in broken ice. Should function in break-up conditions. Would require additional testing to identify limits in Beaufort Sea freeze-up.	Not classified in World Catalog	Current model is harbor-sized; development of a MORICE unit for the Beaufort may require larger scale & additional testing. Testing on original model was conducted in Beaufort Sea.	
N/a	Vibrating unit	unit that may be attached to the bow of a vessel and include a combination of ice-processing belts and skimming systems	Prototype unit developed & tested in Finland; plans to install units on 2 Finnish Coast Guard patrol vessels	Technology not commercially available but in fairly mature development; could be transferred to North Slope if brought to market	Designed to function in Baltic Sea ice environment where rubble ice prevails. Probably well suited for break-up conditions, but continuing ice cover could be a problem.	Not classified in World Catalog	Can be used in rubble ice conditions; can be vessel-mounted on ice breakers. Should be tested under North Slope conditions.	
ExxonMobil	Pneumatic air curtains/ booms	pnuematic air plumes used to release oil trapped under or among ice	Experimental concept; no units commercially available	Technology not developed therefore not transferable	not tested	Not classified in World Catalog	Not avaialable on market, therefore not feasible. Once a unit has been manufactued, it should be tested on the North Slope	

2.4 Ice Management

2.4.1 AVAILABLE TECHNOLOGIES

Ice management systems have been used in Alaska and elsewhere to reduce the concentration of sea ice in areas where mechanical recovery or other spill response activities are taking place. Unlike the other categories considered in this report, ice management does not necessarily involve the use of specialized equipment, but may instead rely on specific tactics or application of existing open water response technologies. The following existing technologies are considered in this report; all are available to some degree in Alaska:

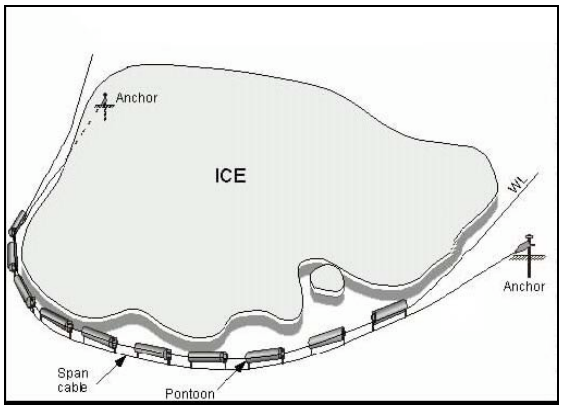
- Fixed boom strategies
- Live boom strategies
- Deflection devices
- Vessels

2.4.1.1 Fixed Boom

Ice booms are affixed permanently in some locations to exclude sea or river ice from areas, facilitate navigation, or protect facilities or infrastructure (Figure 28). Ice booms may be used to exclude ice from an area, or to concentrate ice to accelerate the formation of a stable ice cover. Ice booms should be designed with the capability to relieve the ice load should it become too great. This capability is achieved by constructing the booms such that the flotation elements (i.e., pontoons) will submerge individually which allows the ice to overrun the boom in severe conditions (Abdelnour and Comfort 2001). A typical fixed ice boom consists of one or more span cables, attached at each end to an anchor cable or anchor. Each span has pontoons attached to the cable with chains, one at each end of the pontoon. These chains maintain the cable at about 3 ft below the water surface (Figure 29). The ice-retention capacity of the boom is directly related to its buoyancy. When the ice load exceeds the pontoon resistance capacity, it submerges and the ice drifts over the pontoon. This limits the load on the boom, and reduces the probability of ice damage. The pontoon's buoyancy varies with its size and should be selected based on the desired ice retention capacity of the boom (Abdelnour and Comfort 2001). Traditional oil boom can and has been used for ice management as well, although traditional oil boom usually cannot withstand the same range of ice conditions as ice boom.

Figure 28. Permanent ice boom (left - Lake Erie Niagra River, right – Navaltrie). (Abdelnour and Comfort 2001)

Figure 29. Typical ice boom configuration. (Abdelnour and Comfort 2001)



Most of the published literature on ice booms comes from Canada. Early ice booms used in Canada relied on timber pontoons. More recent models have used steel pontoons, which are larger, more buoyant, and sturdier (Figure 30).

Figure 30. Steel pontoons on ice boom. (Abdelnour and Comfort 2001)

The use of fixed ice booms to manage ice concentrations for spill response, navigation, water intakes, and other purposes is considered to be a mature technology. Oil or ice booms may be used in a variety of configurations to deflect ice. For example, in a scenario where oil is released from an offshore island production facility in relatively shallow water with a steady direction of movement for the ice, a Chevron boom configuration could be anchored upstream from the structure (Figure 31). A similar configuration could be used to direct ice away from surface oil from a subsea pipeline release (Figure 32). In the case of a river or shoreline area where ice is drifting in a constant direction, a fixed deflection boom configuration could be used to direct ice away from on-water recovery operations (Figure 33). Similarly, an exclusion configuration of ice boom could be used upstream of oil boom in a river to keep ice out of the recovery area (Figure 34).

Figure 31. Fixed chevron boom anchored up-current from a production platform spill. (Abdelnour and Comfort 2001)

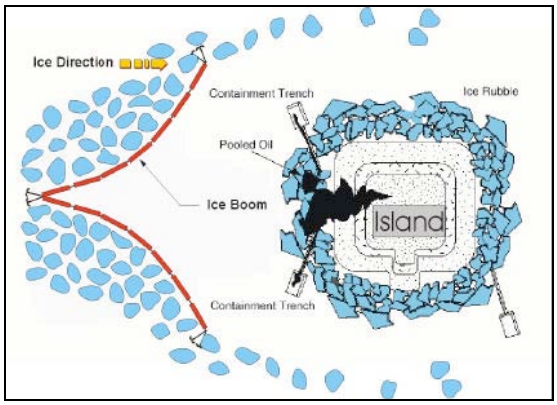


Figure 32. Use of fixed chevron boom to keep ice away from response operations for subsea pipeline release. (Abdelnour and Comfort 2001)

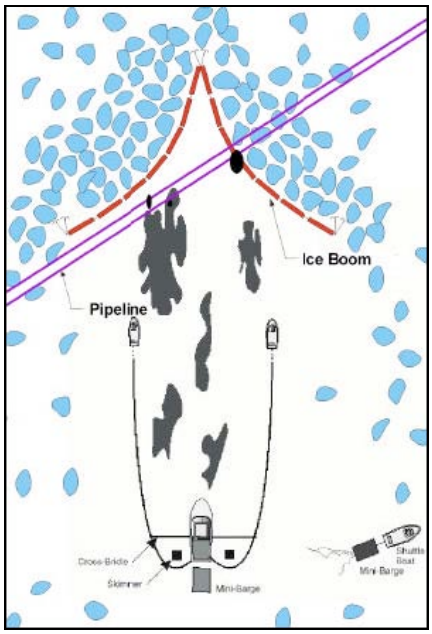


Figure 33. Fixed diversion boom used for ice management. (Abdelnour and Comfort 2001).

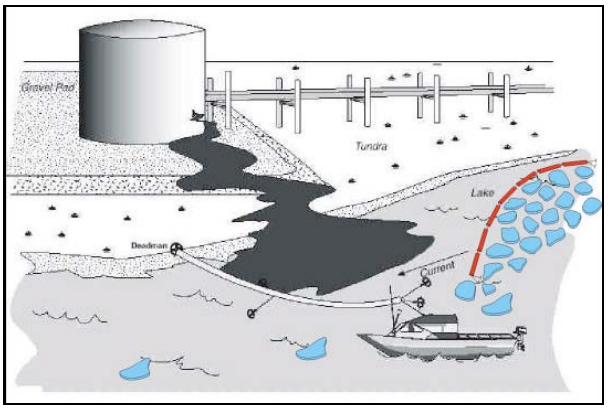
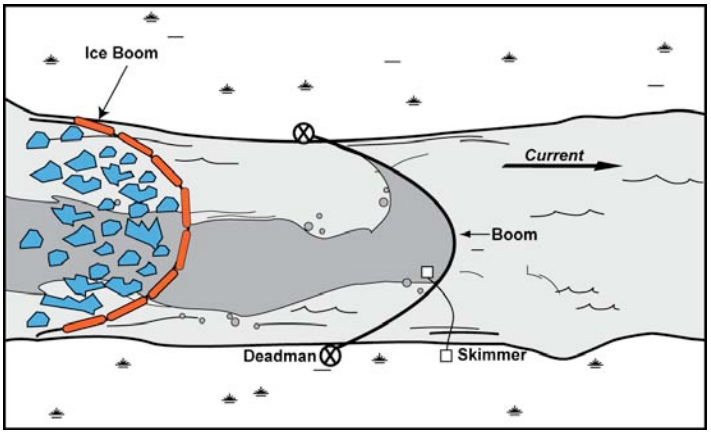


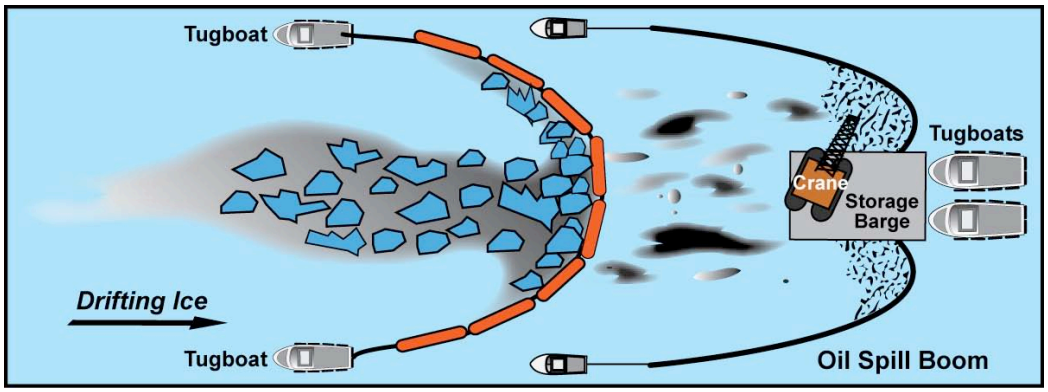
Figure 34. Fixed exclusion boom used for ice management. (Abdelnour and Comfort 2001)



2.4.1.2 Live boom

Live booming techniques could be used in a similar manner to fixed booming techniques to keep ice away from areas where oil recovery is occurring. Figure 35 shows how a U-boom configuration could be used to contain ice while oil underflows the boom into the containment area. However, it is very likely that in such a configuration, the ice would move with the oil under the boom. It is not clear whether Figure 35 has been demonstrated effective in the field.

Figure 35. U-boom used for ice management. (Abdelnour and Comfort 2001)



The effectiveness of ice booming depends to a large extent on the boom's ability to withstand the ice load. Ice load is effected by both the type of water body and the type and concentration of ice coverage. Total force on the boom is a product of wind, current drag, and pack ice forces. The relative impacts of these forces are calculated in detail in Abdelnour and Comfort (2001). With live ice booming, the vessels towing the ice boom will generally require ice-breaking capability, or at least the ability to safely navigate in moderate to heavy ice conditions.

According to one analysis (based on calculations not actual trial data), the three largest vessels on the North Slope (Pt. Barrow, Pt. Thompson, and Arctic River) would be capable of deploying ice boom in ice concentrations ranging up to 30 to 50%. However, the vessels listed in that study are not available on the North

Slope; the three largest vessels on the Slope are actually river class tugs (Kavik River, Sag River, Kuparuk River), which are smaller than the three vessels listed in the study. Therefore, they may not be able to deploy the tactics as suggested by Abdelnour and Comfort 2001). This study recommends that field trials be conducted in Prudhoe Bay to test these capabilities further (Abdelnour and Comfort 2001).

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

The ACS Technical Manual does not include any tactics that use ice booms. Ice management is primarily accomplished using vessels for deflection.

2.4.1.3 Deflection Devices

In addition to ice booms and the grading belts, other types of ice deflection devices have been utilized with varying degrees of success. Figure 36 shows a relatively simple ice deflection device: a metal grate positioned in front of a skimmer to deflect small pieces of ice away from the skimmer. Deflection devices must be carefully positioned so that they deflect ice, but not oil, from recovery devices. During 2000 offshore response trials in the Alaska Beaufort Sea, ice deflection grates were initially observed to deflect "oil" (simulated with popcorn) as well. The grate was raised slightly to avoid encounter with surface oil, which appeared to solve the problem of deflecting surface oil; however, the "oil" that adhered to deflected ice chunks was also deferred away from the skimmer (Robertson and DeCola 2001).

Figure 36. Ice deflection grate. (ADEC photo, K. Ballard 2000)

2.4.1.4 Vessels

Another option for ice management is to use icebreaking or ice-reinforced vessels to reduce ice concentrations or to redirect ice floes. Multi-purpose vessels that can break ice and also provide spill response platforms and temporary storage are used in Finland and other arctic regions, and may prove useful to support mechanical recovery operations in ice-infested waters (SYKE 2004). Ice-breaking vessels may also be used for ice management by breaking up large ice floes and releasing trapped oil. The Finnish vessel *Seili*, which is the first such vessel in service, has a draught of approximately 16 feet (Figure 37).

Figure 37. The Finnish fairway maintenance vessel Seili. (SYKE 2004)

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

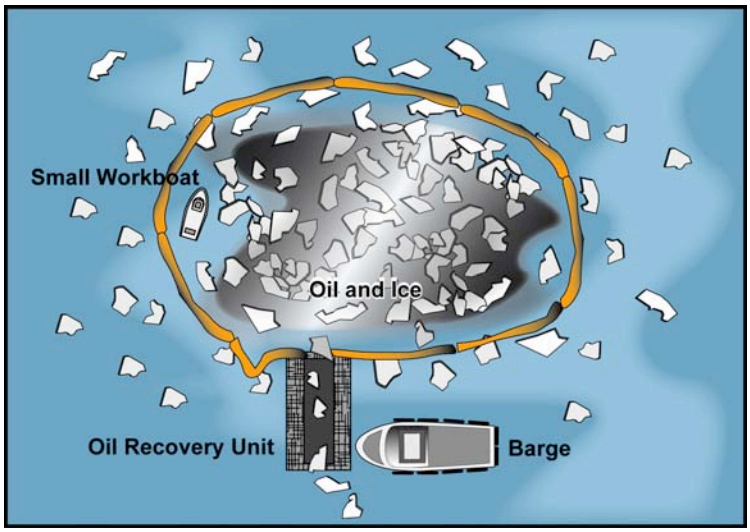
Cook Inlet Spill Prevention and Response, Inc. (CISPRI) has developed vessel maneuvers to open a lead in broken ice next to the oil spill response vessel hull. Using the props and bow thrusters to walk the vessel sideways creates a lead on the downstream side of the vessel. Oil may pool in this lead allowing recovery by skimmers. A fire monitor is also used to wash oil to the skimmer and wash small pieces of ice away from the skimmer. This maneuver was demonstrated to ADEC and the authors of this paper during an exercise on February 15, 2007 (see Figure 38).

Figure 38. Vessel maneuver and fire monitor wash to create a skimming lead. (Nuka 2007)

2.4.1.5 Experimental Technologies

There are no novel ice management technologies reported in the published English language literature, although a 2001 publication describes an experimental ice management system that integrates conventional ice management technologies with ice processing and recovery operations (Narita *et al.* 2001). In this study, researchers conducted tests where they placed a scale model of a specially designed oil recovery unit adjacent to a boomed area to recover oil in ice-infested waters. Within the boomed area, one or more work boats use a bow sweeper to corral the oil and ice and move it toward the recovery unit. Within the recovery unit, an air or water flow curtain is used to separate the surface oil from the ice. Oil is pushed toward the sides of the unit for recovery. Ice pieces remain in the center of the unit where they are processed through water flushing, and "cleaned" ice is returned to the water (Figure 39).

Figure 39. Ice management system combined with recovery and ice processing operations. (Narita et al. 2001)



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

2.4.2 EXPERIMENTAL TECHNOLOGIES

There are no experimental or novel technologies reported in the published literature for ice management. However, there are numerous adaptation and variations on the existing technologies described above.

2.4.3 ASSESSMENT OF ICE MANAGEMENT TECHNOLOGIES FOR THE BEAUFORT SEA

Table 7 considers several ice management technologies or techniques that are readily available on the market and currently stockpiled in Alaska and/or other arctic regions in the context of most the BAT requirements at 18 AAC 75.445(k)(3). (Note that cost is not considered in this analysis).

Ice management is based more in technique/application than technology; therefore, the BAT analysis does not point to any one technology that may be "best" for use in the Beaufort. With ice management, the key element is to have the equipment and training in place to implement one or more techniques in response to the ice conditions as well as the types of recovery operations taking place.

Table 7. Technology Assessment for use of selected ice management systems in the nearshore and offshore Beaufort Sea during ice season.

Type of System	Specifications	Availability (18 AAC 75.445(k)(3)(A))	Transferability to Alaska North Slope (18 AAC 75.445(k)(3)(B))	Effectiveness in ice-infested waters (18 AAC 75.445(k)(3)(C))	Deployment considerations	Feasibility of Beaufort Sea Deployment (18 AAC 75.445(k)(3)(G))	Other considerations
Ice booming	Affixed boom configuration to exclude, divert, or concentrate ice away from oil recovery areas	Tactics are developed; ice boom exists, ACS inventory does not include ice boom	Could be transferred to North Slope	Effective up to operating limits for ice boom (ice load, etc.). Limits likely imposed by other spill response equipment.		Feasible if ice boom can withstand ice load. Deployment is location and situation specific.	
Deflection devices	Use of grates or other materials to divert ice pieces from recovery equipment or areas	broken ice deflection (BID) grate available & tested on N. Slope	Technology available already	Grates can become clogged at higher ice conditions. Should be effective at moderate ice concentrations	Needs additional testing	Feasible in lower ice concentrations; problems with clogging during freeze-up and at high ice concentrations	
Vessels	Use ice breaking or response vessels to break up or divert ice floes	Purpose-built vessels in use in other nations; existing icebreakers and ice tugs in use in Alaska and elsewhere for ice management	Technology could be transferred to North Slope; some vessels on North Slope already used for ice management	Effective up to operating limits for vessel. Need additional testing to identify freeze-up & break-up limits for vessels used as ice management.	Needs additional testing	Feasible, most likely in combination with other ice management technologies	Possible for unintended interference from propellor wash (dispersing or redirecting oil, etc.)
Narita combination ice management system	System combines ice management, ice processing, recovery	Scale model tested; no units commercially available	Technology not developed therefore not transferable	Not enough data	Need testing	Not available on market, therefore not feasible	

2.5 Pumps

2.5.1 AVAILABLE TECHNOLOGIES

This section considers pumps and pumping systems that are rated for use in extreme cold and ice-infested waters, which requires that they be able to pump viscous oils and handle some ice debris. All of the pumps considered use screw auger technology. While other types of pumps (e.g. centrifugal pumps) may be used in association with oil recovery systems in cold climates, they are not capable of processing ice and are therefore not considered in this analysis. Table 8 provides specifications for pumps that may operate in the presence of sea ice and that are available on the market and currently stockpiled in various arctic nations.

Desmi screw auger pumps are the foundation of the North Slope pumping technology based on their well-recognized capability to pump viscous oils and process ice debris. The two models in stock in Alaska are the DOP-250 and the DOP-160 (Figure 40). Another model, the DOP-200, is also commercially available but not currently in the ACS inventory.

Table 8. Specifications for pumps that may operate in the presence of sea ice and that are available on the market and currently stockpiled in various arctic nations.

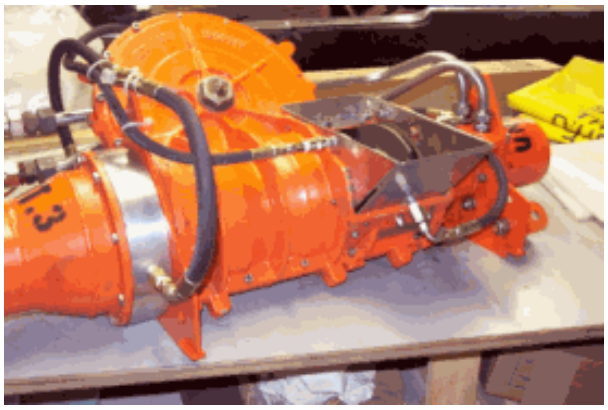
Manufacturer	Model	Pump Type	Capacity (bbl/hr)	Required HP	Comments
Lamor	GT-A 20	positive displacement Archimedes screw	130	44	
Lamor	GT-A 30	positive displacement Archimedes screw	190	44	
Lamor	GT-A 50	positive displacement Archimedes screw	310	71	
Lamor	GT-A 70	positive displacement Archimedes screw	393	60	
Lamor	GT-A 115	positive displacement Archimedes screw	723	89	
Lamor	GT-A 140	positive displacement Archimedes screw	880	76	
Lamor	GT 185	positive displacement Archimedes screw	280	43	
Lamor	GT-260	positive displacement Archimedes screw	630	80	
Qualitech	TDS 150	Archimedes twin screw pumps	220	25	
Qualitech	TDS 200	Archimedes twin screw pumps	41	40	
Qualitech	TDS 250	Archimedes twin screw pumps	820	65	
Ro-Clean Desmi	DOP-250	positive displacement Archimedes screw	790	67	
Ro-Clean Desmi	DOP-160	positive displacement Archimedes screw	190	34	
Ro-Clean Desmi	DOP-DUAL 250	positive displacement Archimedes screw	790	67	twin discharge ports - horizontal and vertical - for skimmer and offloading orientation

Figure 40. Desmi DOP-250 screw auger pump. (Ro-Clean Desmi 2006)

The Desmi screw auger pumps are considered to be high capacity, and are capable of processing ice slush and debris up to 2 inches in diameter. The pump is a positive displacement Archimedes screw pump, hydraulically driven. It features a rotating sealing plate wheel with replaceable sleeves manufactured in polyethylene HD. This pump can pull a deep suction once primed. The Desmi pumps can be fitted with annular injection flanges to introduce steam or water into the oil being pumped and facilitate handling of heavy oils by reducing backpressure in the discharge hose. The annular injection feature is also useful for thawing pumps and lines.

The use of steam or heat to enhance pumping of viscous oils is a fairly effective option for improving pumping and transfer capabilities in ice-infested waters and extreme cold conditions. Techniques for using heat to improve pumping vary from direct heating of the oil before it is transferred, which is not always feasible (Kilpatrick and Saeker 1981), to adding thermal energy to the area of the pump suction (Loesch et al. 2001), to injecting hot water or steam through a specially-designed injection flange mounted at the pump inlet (Hildbak 2001). Steam or hot water injection seems to be the preferred technology in cases where it is not feasible to heat the oil at its source (e.g. in tanks), and like the Desmi, many arctic pumping systems on the market are designed to allow steam or water to be introduced into the system to facilitate pumping of viscous oils. Some studies have shown steam enhancement to be more effective than annular injection of water because the oil tends to flow more easily through the pump and hoses, reducing wear on equipment and downtimes (Cooper and MacKay 2001). Figure 41 shows a screw auger pump with injection devices and steam/hot water lines.

Figure 41. The GT-185 pump with injection devices and steam/hot water distribution lines. The inlet is to the right. (Flemingco 2006)

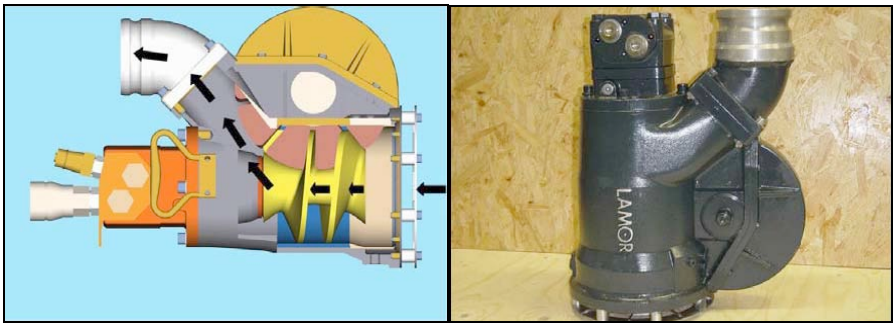


Several other equipment manufacturers offer screw auger pumps capable of transferring viscous oils in ice-infested waters. The basic technology in these pumps is the same as the Desmi pumps used by ACS; however, some of these other pumps have been improved with the addition of multiple cutting knives, redundant sealing discs, and Teflon-impregnated metal.

Lamor markets several models of screw auger pumps – the GT series (GT-185 and 260) and the GT-A series (20 through 140). The GT pumps were the focus of a joint project between the US and Canadian Coast Guards to consider pumping of viscous oils. Through this project, a system was designed to fit the GT-185 with inlet and discharge side steam/hot water injection devices (Figure 41). The studies, conducted in 2001, reported significant improvements in pumping capabilities over the model without the special fittings (Flemingco 2006).

Lamor GT-A pumps are also fitted with a steam/hot water injection flange to facilitate pumping of viscous oils. The pump is marketed specifically for use in arctic environments. The pump comes in six models – the GTA 20, 30, 50, 70, 115, and 140, which correspond to their general capacity in meters/hour. They are designed for use with skimmers or as offloading/transfer pumps (Figure 42).

Figure 42. Lamor GTA pumps.



Foilex, a Swedish manufacturer, also has a line of screw auger pumps designed for use with viscous oils and in ice-infested waters. Foilex TDS pumps (marketed in the US by Qualitech) may be used to transfer recovered liquids, or may be incorporated into weir skimming systems. The TDS-200 and TDS-250 models are heavy duty pumps; the TDS-150 is a smaller, lightweight high-capacity pump (Figure 43).

Figure 43. Foilex TDS-200 screw auger pump. (Foilex 2006)

2.5.2 EXPERIMENTAL TECHNOLOGIES

Research and development of pumping viscous oils has focused primarily on enhancing existing technologies (primarily the screw auger pumps) to be able to handle oils with high viscosity or extreme rheological behavior. Continued research into viscous oil pumping has been identified as a priority for the JIP, although no specific projects or technologies have been proposed. It is likely that manufacturers will continue to refine and improve annular injection systems.

2.5.3 ASSESSMENT OF PUMPING TECHNOLOGIES FOR THE BEAUFORT SEA

Table 9 compares pumps that are readily available on the market and currently stockpiled in Alaska and/or other arctic regions in the context of most the BAT requirements at 18 AAC 75.445(k)(3). (Note that cost is not considered in this analysis).

The BAT analysis reflects available information compiled from a variety of sources. One frustration in compiling this data is that the World Catalog does not provide any data regarding the use of specific equipment in ice conditions. While the ASTM operating environment classifications include broken ice, only the categories of open water, protected water, and calm water are used to classify skimmers in the Catalog.

Table 9. Technology Assessment for use of selected pumps in the nearshore and offshore Beaufort Sea during ice season.

Manufacturer	Model(s)	Specifications	Availability (18 AAC 75.445(k)(3)(A))	Transferability to Alaska North Slope (18 AAC 75.445(k)(3)(B))	Effectiveness in ice-infested waters (18 AAC 75.445(k)(3)(C))	Feasibility of Deployment in Beaufort Sea (18 AAC 75.445(k)(3)(G))	Other considerations
Ro-Clean/Desmi	Screw auger pumps (DOP 160, 200 & 250)	positive displacement Archimedes screw pump, hydraulically driven.	Available on market; 2 DOP-160 units & 17 DOP-250 units in ACS inventory	Already in use	Work well in slush ice and some debris. Should work in freeze-up in low to moderate ice and in most break-up conditions, not in continuous coverage.	Can be used with most skimmers in ice-infested waters at least up to skimmer limits. Requires a hydraulic power pack and should be fitted with an annular injection system for viscous fluids.	These pumps have cutting knives on the pump impellors and can be reversed if clogged .Even in systems capable of handling debris, it is important to limit the amount of ice that enters the pumping system as it can clog hoses.
Lamor	Lamor GT screw auger pumps	Archimedes screw pump	Available on market; not in ACS inventory	Tested with adaptations for viscous oil pumping; used by other response co-ops in arctic nations	Designed for use in cold temperatures with some ice debris. Should be comparable to other screw auger pumps.	Should be comparable to other screw auger pumps; can be used with most skimmers. Requires a hydraulic power pack and should be fitted with an annular injection system for viscous fluids.	These pumps have cutting knives on the pump impellors and can be reversed if clogged. Even in systems capable of handling debris, it is important to limit the amount of ice that enters the pumping system as it can clog hoses.
Qualitech	Foilex TDS screw auger pump	screw pump	Available on market; not in ACS inventory	Could be used on North Slope	Should be comparable to other screw auger pumps	Should be comparable to other screw auger pumps; can be used with most skimmers. Requires a hydraulic power pack and should be fitted with an annular injection system for viscous fluids.	These pumps have cutting knives on the pump impellors and can be reversed if clogged. Even in systems capable of handling debris, it is important to limit the amount of ice that enters the pumping system as it can clog hoses.
Lamor	Lamor GT-A pumps	positive displacement Archimedes screw pump will annular water injection	Available on market; not in ACS inventory	Could be used on North Slope	Designed for use in cold temperatures with some ice debris. Should be comparable to other screw auger pumps	Should be comparable to other screw auger pumps; can be used with most skimmers. Requires a hydraulic power pack.	These pumps have cutting knives on the pump impellors and can be reversed if clogged. Even in systems capable of handling debris, it is important to limit the amount of ice that enters the pumping system as it can clog hoses.

3. Analysis

This section considers the mechanical recovery technologies and systems described in Section 2 in terms of potential effectiveness in the Beaufort Sea under a range of sea ice conditions. For much of this equipment, there is limited data available from actual deployment in ice-infested waters, therefore many of the evaluations are based on field trials or data from scale models.

3.1 Challenges of Mechanical Recovery in Ice-infested Waters

Compared to temperate, open water conditions, the ability to clean up oil spills in the presence of sea ice is extremely limited and conditional. In dynamic ice conditions, the window-of-opportunity where one technology may be favored over another can be extremely brief. In considering the efficiency or capabilities of individual technologies, it is important to recognize that most mechanical recovery equipment is deployed as part of a tactic involving multiple types of equipment, and that a failure of any type of equipment within that system can compromise the effectiveness of the technology. Often, technology may be only one of several limiting factors in determining the effectiveness of a cleanup option. Cold climate efficiency losses, operational requirements, and safety limitations can also impact the efficiency of both an individual technology and the overall response.

In some cases, planning assumptions about the operating limits of mechanical recovery equipment or systems in ice-infested waters have been challenged by actual deployment tests. For example, the limit to mechanical recovery with containment booms and skimmers in ice-infested waters is generally considered to be 20-30% ice coverage (Figure 44). However, the 2000 offshore response exercises in the Alaska Beaufort Sea demonstrated that the actual operating limits were closer to 10%, and that during fall freeze-up, ice conditions as low as 1% constituted the operating limit for a barge-based mechanical recovery system using conventional boom and skimmers In addition to ice coverage, the characteristics of the ice regime are an important determinant of response efficiency. The 2000 offshore exercises demonstrated that fall ice conditions (freeze-up) can be more challenging than spring break up (Robertson and DeCola 2001, NRC 2003a). Therefore, 10% ice coverage in fall may pose different limits than 10% coverage in spring. These complexities make it difficult to develop meaningful guidelines for when certain technologies may or may not function.

When interpreting efficiency estimates for mechanical recovery equipment, another important consideration is that recovery capacities (the actual amount of oil removed per unit time) of the different mechanical recovery systems vary widely. Some systems may be able to operate in moderate to high ice concentrations, under the right conditions, but may have comparatively low recovery capacities or be limited to operation in areas with contained, thick oil slicks.

Figure 44. Indication of expected effectiveness of mechanical recovery methods as a function of ice coverage (adapted from Evers et al. 2006).

		Ice Coverage									
Response method	**Open water**	**10 %**	**20 %**	**30 %**	**40 %**	**50 %**	**60 %**	**70 %**	**80 %**	**90 %**	**100 %**
Mechanical recovery:											
Traditional configuration (boom and skimmer)											
Use of skimmer from icebreaker											
Newly developed concepts (Vibrating unit; MORICE)											

Other factors that may reduce the window-of-opportunity for using mechanical recovery technologies in ice-infested waters include:

- Decreased daylight during winter hours reducing the operational period.
- Low visibility due to fog banks or low ceiling can limit spill tracking and also make it difficult for vessels to spot ice floes.
- Cold temperatures may reduce efficiencies of response personnel due to heavy clothing and the need for more frequent breaks to avoid hypothermia.
- Cold temperatures may cause machinery to freeze up or fail, and may cause brittle failure of some metals.
- Icing conditions on vessels may make vessel-based spill response slower or unsafe.

It is important, in researching and developing new mechanical recovery technologies for use in ice-infested waters, that these potential efficiency losses are also addressed, in order to maximize recovery efficiencies. Field trials during a range of environmental conditions are an excellent way to identify and address many of these efficiency losses, which are generally not considered during laboratory or wave tank trials.

3.2 Containment

The major challenge to containment of oil spills in ice-infested waters is the impact of ice floes and ice pieces on the boom. All oil booms will eventually fail once sea ice reaches a certain concentration, due to the strain of the ice on the boom causing the boom to tear or the force of the ice lifting the boom from the water surface. As with most oil spill response technologies, the growing ice cover and grease ice common during freeze-up are more challenging for most oil booms.

In considering available and experimental containment technologies for use in Beaufort Sea ice seasons, there is only one type of boom that is available on the market and not currently stockpiled in Alaska: Norlense AS offshore booms. Information supplied by the manufacturer indicates that this boom works well in ice-infested waters, and is frequently used for preventative booming of tankers

during loading in Norway. The boom has a built-in hose system that can be used to warm the boom and melt ice and snow, which might improve its function under certain conditions. However, a source for the hot water is required, and this will increase the size of the vessel necessary to deploy the boom. There is no definitive data available to recommend the Norlense over the Ro-boom currently stockpiled by ACS. Additional studies might be useful to compare Norlense, Ro-boom, and other heavy duty booms under a range of ice conditions to better define their strengths and weaknesses.

Research and development in this area continues to focus on winterization of existing technologies rather than the development of novel concepts. Some improvements to boom technology have been realized by using new, more durable materials to construct booms intended for use in ice-infested waters.

Table 3 (Section 2) compares the containment booms discussed in this paper based on the technical criteria in the State of Alaska BAT regulations at 18 AAC 75.445(k)(3).

3.3 Recovery

Skimmer capabilities diminish quickly in the presence of sea ice. Ice concentrations as low as 1% have been shown to effectively clog some skimmers. Like boom, skimmers function slightly better during break-up conditions than during freeze-up. Oleophilic brush pack or drum brush skimmers seem best suited to operations in ice, presuming concentrations remain low. Rope mop skimmers may also work for recovering pooled oil in higher ice concentrations. Both technologies work best in batch modes, which makes them suited to contained pools of oil but not to large-scale cleanup operations. Weir skimmers have limited applicability in ice because they tend to clog at relatively low ice concentrations, although researchers have shown some interest in combining weir skimmers with brush units to operate more effectively in ice.

In recent years, several skimmers have been developed and marketed for use in arctic conditions. The Lamor Recovery Bucket (LRB) and Arctic Skimmers were both designed for use in ice-infested waters. While the arctic skimmer, which came about because of MORICE, is quite new to the market and there is limited test data available, the recovery bucket has shown significant promise in cleaning up contained pools of oil in and among ice. The "bucket" portion of the skimmer is an excavator that can be used to remove ice and other debris. The oleophilic brush drum works effectively in slush ice. While more data regarding the bucket skimmer would be useful to better understand its potential efficiency and limitations in freeze-up and break-up conditions, there is sufficient data regarding its effectiveness in ice-infested waters to consider adding units to the ACS stockpiles. It might be useful to test both of the Lamor skimmers – the LRB and arctic skimmer – in the Beaufort Sea. A smaller version of the bucket skimmer (lower weight) might be particularly suited to the Beaufort Sea because it would be more feasible to deploy in nearshore areas.

The Desmi DBD (disc brush drum) skimmer has also been demonstrated effective in ice-infested waters. However, this skimmer is marketed primarily for use in harbors and nearshore environments. Additional data is needed to determine whether this skimmer would be a feasible option for offshore response in the Beaufort, or whether it would out-perform the Lamor brush pack already in ACS stockpiles.

The UCSB novel skimmer surface concept, which is now being manufactured by Elastec, represents a promising tool for marine recovery in ice. The grooved drum skimmers are relatively small and portable, and could be deployed in pockets of icy water. The combination of the grooved drum and custom-fitted scraper appear to be able to process slush ice upt to at least 30% concentration. As with all skimming systems, field trials are important to better delineate the operational parameters of the skimmer as part of a larger marine recovery system. Also, the skimmer's capabilities and limitations should be explored across a range of ice conditions.

Table 5 (Section 2) compares the skimmer discussed in this paper based on the technical criteria in the State of Alaska BAT regulations at 18 AAC 75.445(k)(3).

3.4 Ice processing

Unlike containment and recovery technologies, which were developed for use in open waters and require some adaptation or winterization for use in ice-infested waters, ice processing systems are designed specifically to address some of the challenges of cleaning up oil spilled to broken sea ice. Ice processing systems address a common challenge in cleaning up arctic marine spills: oil often adheres to ice, making it especially difficult to recover.

The ice processing technologies on the market or in development use a range of technologies to separate oil from ice and then concentrate the oil for recovery. The two market-ready technologies were developed by Lamor. The Lamor Ice Cleaner (LIC) was actually first developed and tested fifteen years ago, and uses a combination of water-spraying nozzles and two sets of brushes on conveyor belts to clean the ice and collect oil for recovery. One limit to this technology that might preclude its applicability in the Beaufort Sea is that it requires a vessel with a deep draught and relatively large hull. While initial field trials showed that the system operated well in relatively high ice concentrations, the technology has not been put to use beyond the initial unit in Finland. However, Lamor does offer the unit as part of its arctic response equipment.

The Lamor Oil Ice Separator (LOIS) builds on some of the concepts used in the LIC, and combines an advancing skimmer with a built-in ice processing unit that also attaches to the side of a vessel. An oscillating ice grid cleans the ice and separates the oil and channels it to a recovery area. The LOIS can be mounted on any response vessel, and although it has been developed primarily for vessels with built-in oil recovery systems, it can also be delivered with a Lamor brush skimmer installed. The system is in use on one vessel in Finland, with plans to develop two others. Although it is available on the market, the units appear to be custom-built

and might therefore require some lag time before one could be acquired and deployed in Alaska. Also, the units function most efficiently when they advance at slow speeds (0.7 kts or less); therefore, the encounter rate remains rather low.

According to the manufacturer, the LOIS operates effectively in ice-infested waters conditions. However, there is not enough field data to determine the capabilities and limitations of the system in freeze-up and break-up conditions. The system was designed and is primarily used in shipping channels, where rubble ice is present (smaller ice chunks than are common in the Beaufort). The LOIS would not likely be operable in the nearshore Beaufort Sea, but might be worth investigating for use offshore if oil exploration and production proceeds in new lease areas. However, the LOIS is a significant investment to make without better data regarding its performance in Beaufort Sea ice conditions.

The MORICE unit has already been tested on the Alaska North Slope, although the unit tested was a smaller, harbor-size model than would be necessary for offshore operations. As with the LOIS, the size of ice pieces encountered during Beaufort Sea break-up are the main hindrance to the MORICE concept. While the unit is capable of processing small ice chunks, a significantly larger scale would be required to deal with the larger ice pieces in the Beaufort. At that scale, the vessel would not be functional in the nearshore.

The vibrating unit that has been tested and developed in Finland is especially well-suited for its operating environment in the Baltic Sea, where rubble ice predominates. The system does not function well in a continuous ice cover but might be able to work in broken ice concentrations that exceed conventional boom and skimmer operations. Additional testing of this unit in Beaufort Sea ice conditions would be useful for further evaluation, specifically focusing on the maximum ice piece size that the unit could process.

The pneumatic air curtain concept is still in the research and development stages and is therefore not transferable to the Beaufort Sea at this time.

Table 6 (Section 2) compares the ice processing systems discussed in this paper based on the technical criteria in the State of Alaska BAT regulations at 18 AAC 75.445(k)(3).

3.5 Ice management

Ice management is as much tactic as technology. Existing technologies include ice booms, deflection grates, and the use of vessels to break up and divert ice floes. A combination of one or more of these technologies may provide the best approach to ice management in the Beaufort Sea, particularly during transitional ice seasons.

The use of ice booms in either fixed or live configurations can exclude most sea ice from areas where oil recovery is taking place. The key to successful positioning and maintenance of ice boom is to select the proper configuration based on the ice movement, ice concentration and thickness, current, wind, and other on-scene

conditions. An understanding of ice load is important to selecting the proper boom angle and length. Most of these issues can be addressed through field trials and on-water training exercises where responders experiment with different boom configurations in a variety of ice conditions. Unlike most other mechanical recovery systems, ice management can be practiced without the use of oil, as the purpose of the tactics is to redirect ice. In reviewing the ACS equipment inventory, no ice booms are listed. If ice booms are not in stock on the North Slope, it might be worth testing a few models and then stocking the most appropriate type.

Deflection devices, such as the BID grate used during the 2000 North Slope offshore exercises, are fairly low-tech and can be engineered and adjusted on an *ad hoc* basis. Like ice booms, the key to identifying effective ice deflection configurations may be to experiment through trial and error. CISPRI has also demonstrated that fire hoses can be used to deflect ice from recovery areas.

The use of vessels to manage ice has both benefits and drawbacks. This is a readily transferable technology that could be accomplished by any ice breaking vessel without any specialized equipment. However, improperly executed ice management can cause more harm than good by redirecting oil away from recovery areas or creating mixing energy that disperses the oil below the surface. Additional work with ice management vessels in the Beaufort Sea under a range of ice conditions might be useful to yield rules-of-thumb regarding ice management vessel tactics and maneuvers.

The only experimental technology considered in this report is a combination ice management/recovery system that is not market-ready. It is unclear whether this technology represents a significant improvement over existing ice management technologies.

Table 7 (Section 2) compares the ice management systems discussed in this paper based on the technical criteria in the State of Alaska BAT regulations at 18 AAC 75.445(k)(3).

3.6 Pumps

Oil recovered from ice-infested waters may be highly viscous due to low ambient temperatures, and may contain ice chunks and other debris. Several pumps and pumping systems have been developed to address the challenge of pumping viscous oils and oil/ice mixtures.

Screw auger pumps seem to be the technology of choice for use with viscous oils where slush ice and debris are present. ACS stocks the Desmi 250 screw auger pump, which is considered by North Slope operators to be BAT. The Desmi is generally comparable to other screw auger models, with the possible exception of the newer pumps (GT-185 and Lamor GTA) that have integrated annular injection systems to heat viscous oils and improve capacities. The Desmi pumps are capable of being retrofitted for annular injection, but it is unclear whether they have been.

Table 9 (Section 2) compares the pumps discussed in this paper based on the technical criteria in the State of Alaska BAT regulations at 18 AAC 75.445(k)(3).

4. Recommendations

On the basis of the data presented in this report, the authors offer the following recommendations to ADEC regarding the potential applicability of existing or experimental technologies to oil spills in the Alaska Beaufort Sea. In many cases, additional testing or field trials are recommended.

4.1 Mechanical Recovery Technologies and Equipment

The analysis in this report shows that there are no "breakthrough" mechanical recovery technologies for ice-infested waters. However, equipment manufacturers in other arctic nations have developed and marketed certain pieces of mechanical recovery equipment that *may* represent an improvement over some of the technologies in use in the Alaska Beaufort Sea. Several experimental technologies also merit further attention for their potential applicability during ice season in the nearshore and/or offshore Beaufort Sea.

Table 10 summarizes the existing and experimental mechanical recovery technologies described in this report that *are not* currently stockpiled in the Alaska North Slope but that *may* improve response capabilities in the nearshore or offshore Beaufort Sea when sea ice is present.

Table 10. Promising technologies for mechanical recovery of oil in ice-infested waters not currently stockpiled in Alaska.

Equipment Type	Equipment Model	Operating Environment(s)	Description	Potential Improvements over similar equipment	Other considerations	Recommendations
Containment boom	Ro-Boom HD Series	Open water	Heavy duty inflatable curtain boom	May withstand ice impacts better than standard Ro-boom.	Heavy boom requires larger vessels for deployment; probably not suited to nearshore operations but may be appropriate offshore.	Consider replacing old Ro-Boom with HD as equipment is phased out, if HD demonstrated effective in Beaufort
Containment boom	Norlense-AS series offshore boom	Open water	Heavy duty pressure-inflatable curtain boom designed for use in ice-infested waters. Range of sizes available.	Boom tested and used in ice-infested waters. It has self-heating mechanism (hose) that may reduce icing/snow load on boom.	Comparable in size to Ro-Boom. Not included in 2004-2005 World Catalog so all specifications come from manufacturer.	Test in Beaufort Sea to determine whether significant improvement over Ro-Boom.
Containment boom	Aquaguard airflex series	Protected water	Pressure-inflatable curtain boom	Boom not specifically designed for use in ice-infested waters but fabric has comparatively higher tensile strength than other protected water booms of similar size.	Unproven in ice-infested waters.	Test specifically in nearshore Beaufort when ice is present.
Skimmer	Combination weir/brush skimmer	protected or open water	brush drum skimmer mounted on top of weir skimmer to reduce ice clogging of weir and maximize recovery	Not yet tested in ice, but combines higher recovery rate of weir skimmer with ice capability of brush drum.	Unproven in ice-infested waters. Further testing needed. Technology available on market but not listed in World Catalog.	Monitor testing to determine whether appropriate for use in ice-infested waters.
Skimmer	Ro-Clean/Desmi DBD (disc brush drum) skimmer	some models rated for protected water, some models rated for open water	Disc/brush drum skimmer that can be used in both stationary and advancing mode	Have been used in high broken ice conditions in harbors. Relatively small size allows for range of deployment configurations.	Not tested in offshore broken ice conditions. Manufacturer recommends use in ice in harbor, but no specific data to recommend DBD over other brush skimmers already in ACS inventory.	Monitor testing to determine whether appropriate for use in ice-infested waters.
Skimmer	Lamor Arctic Skimmer					Test in Beaufort Sea under a range of ice conditions to identify any advantages over brush drum skimmers.
Skimmer	Lamor Recovery Bucket (LRB)					Test in Beaufort Sea under a range of ice conditions to identify any advantages over brush drum skimmers.
Skimmer	Elastec grooved skimmer (UCSB concept)		drum skimmer with interchangeable oleophilic brush drums with grooved or smooth surfaces and various skimmer materials to optimize recovery rates	Affords opportunity to tailor skimmer surface based on oil properties, environmental conditions.	Not yet tested in ice. Tank trials with sea ice scheduled for February 2007. Recommend field trials if tank trials favorable. Preliminary tank tests in ice show skimmers work well up to 30% slush ice. Formal results pending.	Encourage additional testing in wave tanks and field trials to determine whether novel skimmer surfaces enhance recovery in ice and extreme cold conditions.
Ice management	Ice booming	open or protected water	Ice boom is positioned to exclude ice pieces from areas where recovery is taking place.	No comparable equipment/technology for open water.	Can be tested without oil. Effective ice management can significantly increase encounter rates and skimming efficiencies.	Test ice management tactics using ice boom during future field trials.
Ice management	Vessel deflection and ice management	open or protected water	Ice-capable vessels are used to deflect or move ice pieces away from areas where recovery is taking place.	No comparable equipment/technology for open water.	Can be tested without oil. Effective ice management can significantly increase encounter rates and skimming efficiencies.	Test ice management tactics using vessel deflection during future field trials.
Ice processing	LOIS or similar model	protected water	advancing skimming system with a built-in ice processing unit that may be attached to the side of a response vessel	integrated skimming system designed for use in presence of sea ice	Not ideally suited for Beaufort Sea. The LOIS is primarily used in shipping channels where rubble ice is more common. Ideal advancing speed is 0.7 kts which reduces encounter & recovery rates.	Consider applicability to Beaufort Sea offshore at future time; not recommended for nearshore use due to size. Additional information about maximum ice piece that the system can handle would be useful to Beaufort analysis.
Pumps	Screw auger pumps with built-in annular injection systems (i.e. GT-185 or Lamor GTA)	n/a	Positive displacement archimedes screw pumps with annular injection systems	Annular injection of steam or hot water may enhance capability to pump viscous fluids at cold temperatures.	Need to have a source for steam or fluid to be injected throuh annular ring system, which generally requires a larger response platform.	ACS does have annular injection systems that can be used with their pumps. Do not recommend additional focus on pumping systems at this time.

4.1.1 CONTAINMENT

There is only one ice-capable open water containment boom on the market that is not currently stockpiled by ACS – Norlense AS. Since this boom is marketed specifically for use in ice-infested waters, it should be considered for use in Alaska. There is not enough data to definitively recommend this boom over Ro-boom or others that ACS uses, but it should be considered for testing under a range of Beaufort Sea ice conditions for comparison against existing stockpiles. The major difference between Norlense AS and Ro-boom is the heating mechanism that is part of the Norlense AS boom. Since Norlense AS is not included in the 2004-2005 World Catalog, it is difficult to compare tensile strength and other parameters with other open water booms. The manufacturers did not respond to a request for information regarding the tensile strength and tear strength of the Norlense AS fabric.

Several manufacturers offer protected water booms with high tensile strength that may be suitable for use when sea ice is present in the nearshore Beaufort Sea. Aquaguard Airflex boom has the highest tensile strength of the protected water booms considered in this report. Since these booms are smaller and lighter and may be easier to deploy from shallow-draft vessels, they should be field tested in the Beaufort Sea under a range of ice conditions.

There are no experimental concepts in containment boom technology reported in the English-language literature. Research and development in this area continues to focus on winterization of existing technologies.

4.1.2 RECOVERY

There are a few arctic skimmers currently on the market that are not stockpiled in Alaska. Most of the ACS skimmers that would be appropriate for use in and among sea ice (i.e. Lori brush drum) are stationary skimmers that could be positioned in leads. In such cases, the major limiting factor to recovery rate and effectiveness would be the interference of ice pieces. If ice can be managed away from the skimmer, efficiency would likely be improved.

Several of the arctic skimmers described in this report are also stationary skimmers, although they are designed to process slush and ice together with oil. The Lamor Arctic Skimmer also uses steam injection to heat the oil collected in the hopper and facilitate flow to the pump. However, the size of the ice pieces that can be processed by these arctic skimmers is an important consideration in determining their potential advantage over other "non-arctic" stationary skimmers. With all stationary skimmers, oil recovery generally occurs in "batch" mode, leading to relatively low recovery capacities.

Of the arctic stationary skimmers, the Lamor LRB shows promise for use on the North Slope because it is easily positioned into open areas using a crane or hydraulic arm. However, the LRB requires a fairly large deployment platform so it is probably not feasible for use from small response vessels in the nearshore.

Advancing skimmers do not generally work well in the presence of sea ice, although some of the ice processing concepts (see Section 4.1.3) integrate ice deflection into an advancing system to allow for recovery in the presence of broken ice pieces. Again, however, the size of the ice chunks may be a limiting factor for such technologies in the Beaufort Sea.

Researchers continue to work toward improving skimming capabilities in and among sea ice. The newly available grooved surface drum skimmers manufactured by Elastec show initial promise in certain ice conditions. This technology offers a new option for recovery of oil in ice-infested waters by allowing responders to tailor the skimmer surface to the type of oil spilled and possibly the type and characteristics of sea ice present. Additional tests, under field conditions, will help to better delineate the capabilities and limitations of this technology.

4.1.3 ICE PROCESSING

Several ice processing technologies have been developed and put to use in Finland (LOIS, LIC, vibrating unit). One or more of these technologies (most likely the LOIS) could be tested in the Beaufort Sea to determine whether they offer improved mechanical recovery efficiencies. One potentially limiting factor is the maximum size of ice piece that these systems can process. Since broken ice pieces in the Beaufort are generally quite large (the size of a room or building). The LOIS and MORICE units were both designed to handle much smaller pieces of ice.

Since ice processing technologies as they exist today require large vessels to deploy them, they may not be appropriate for nearshore response in shallow areas. However, if oil exploration and production is initiated further offshore in newer lease areas, ice processing technologies designed for deeper waters may be more appropriate for use in the Beaufort Sea.

4.1.4 ICE MANAGEMENT

Ice management in the Beaufort Sea is accomplished primarily by deflection of ice using vessels or grates, or avoidance of areas where ice is present. Ice booming is another technique that has been used successfully in other areas and should be considered for testing in the Beaufort Sea. Since oil recovery rates are enhanced when ice is managed away from recovery areas, the improvement of ice management and use of ice booming may improve overall mechanical recovery in ice-infested waters.

One challenge with using stainless steel ice booms is the size and draft of vessel required to position them. However, conventional oil boom or smaller ice booms may be appropriate for ice management in the shallow nearshore areas.

Ice management is more a tactical issue than technological, and unlike other mechanical recovery techniques, it can be effectively practiced without the use of oil or simulated oil. Future field trials and training courses should consider the use of ice boom in varying configurations as a method to enhance mechanical recovery. Ice deflection technologies and vessel ice management tactics should

also be explored. Fire hoses, like CISPRI has used, may also provide some ice management benefit in the Beaufort. ADEC should consider whether ice boom should be stockpiled on the North Slope to facilitate ice management.

4.1.5 PUMPS

Screw auger pumps are the favored technology for viscous oils in ice, and the Desmi 250 pumps in stock on the North Slope are comparable to others on the market, with the possible exception of their compatibility with annular injection systems to heat viscous fluids. North Slope operators' BAT analyses should consider whether the Lamor GTA or GT-185 offer enhanced capabilities due to their integrated annular injection systems.

4.1.6 DEPLOYMENT CONSIDERATIONS

Vessels are critical to the deployment of response equipment in the Beaufort Sea; yet, vessel classification schemes do not really account for the types of response vessels that are required to deal with nearshore Beaufort ice conditions; the shallow waters preclude Class 1 and 2 vessels, which are typically favored for response where sea ice is present.

4.2 Regulatory and Policy Considerations

4.2.1 INCENTIVES FOR TESTING AND PURCHASING NEW EQUIPMENT

The age and condition of response equipment is important to consider in evaluating the technological and operational capabilities of a system. Because there are few incentives in state or federal regulations to replace equipment ahead of amortization schedules, the purchase of new equipment is an infrequent occurrence.

Many of the technologies (particularly skimmer) that show promise for use in ice-infested waters are meant for batch recovery of contained oil in pits or ice leads, and not for large-scale, high capacity recovery. Since the recovery capacities for "ice-capable" systems and equipment may seem very low when compared to open water systems, the incentive to purchase such "less efficient" equipment may not be clear.

While at first glance, there do not seem to be many clear incentives toward acquiring new equipment for use in ice-infested waters, a number of state regulations, policies, and agreements do in fact contain incentives or directives for improving mechanical response technologies in Beaufort Sea ice conditions. As development proceeds in offshore lease areas, these regulations may be useful to promote improved mechanical response capabilities during ice season.

- The Alaska Best Available Technology (BAT) regulations at 18 AAC 445(k) state that a technology or system will be considered BAT if "the technology of the applicant's oil discharge response system as a whole is appropriate and reliable for the intended use as well as the magnitude of the applicable response planning standard." Technologies that are intended for use in ice-infested waters should be appropriate for use in the ice conditions that are

reasonably expected to be encountered. Drills and exercises that demonstrate that certain equipment or technologies are not "appropriate and reliable" for use in the ice-infested Beaufort Sea could be used as incentives to drive additional testing and potentially acquisition of new technologies.

- Realistic maximum response operating limitation (RMROL) regulations at 18 AAC 75.445(f) give ADEC the authority to require "specific temporary…response measures" to reduce the risk or magnitude of a discharge during periods when environmental conditions might preclude mechanical recovery. Therefore, ADEC may require improved or supplemental technologies and tactics appropriate for use in ice-infested waters as RMROL measures. Conversely, the capability to use new or improved mechanical recovery technologies under certain ice conditions might shorten the duration of the RMROL period, which would benefit the operator.

- The Response Planning Standard (RPS) regulations at 18 AAC 75.434 (a) require an operator to contain, control and clean up **within 72 hours** that portion of the RPS that enters open water and to contain or control within 72 hours, and clean up within the shortest possible time, that portion of the response planning standard volume that enters a receiving environment other than open water. However, the equipment that most effectively contains and controls an oil spill in ice-infested waters may not be the same equipment that would work best in open water. While the 72-hour standard for open water cleanup has led response organizations and planholders to favor mechanical recovery systems with high recovery capacities, the best systems for use in ice-infested waters may have lower overall recovery capacities but might work much more effectively in the presence of sea ice. They might include additional components such as ice management technologies or tactics to reduce the amount of ice present in the recovery area and ice-capable containment, recovery, and pumping technologies that can be deployed in ice-infested waters, even if their overall recovery rates are significantly lower than comparable systems in open, ice-free waters. Containment and recovery systems intended for use in ice-infested waters should be evaluated based on their ability to, at a minimum, *contain and control* the RPS volume within 72 hours, using technologies that are most effective in the presence of sea ice and including additional components – such as ice management – that may not be included in open water response systems.

- Finally, the Alaska North Slope Charter Agreement, while not a binding regulation, emphasizes the importance of continual improvement of spill response capabilities in the Beaufort Sea. The agreement states that BP and CPA will "work to improve and protect the environment on the North Slope, including a commitment to North Slope Spill Response to support an Arctic spill response research and development program that is jointly

agreed to by ADEC, BP and CPA." Since the Beaufort Sea ice environment is unique, the response technologies needed to improve mechanical recovery in this environment may also need to be purposefully designed with Beaufort Sea ice conditions in mind.

Ice conditions in the Beaufort Sea are highly dynamic during freeze-up and break-up, both over time and in different environments. At the same time, different mechanical recovery technologies and systems may be particularly suited to a certain range of ice conditions. This can create a problem not only in stocking equipment, but in selecting and deploying the appropriate technologies for the ice conditions. To a certain degree, arctic response organizations should have some variability in their equipment inventory to address the changing parameters of the ice environment. ADEC should consider this need for heterogeneity in equipment stockpiles and actively promote the purchase and stockpiling of ice-capable response equipment through enforcement of regulations and policies.

4.2.2 LOGISTICAL SUPPORT AND DEPLOYMENT CONSIDERATIONS

Efforts to improve mechanical recovery capabilities in ice-infested waters should consider not only technological issues, but also operational, logistical, and safety considerations, which may also impact response efficiency. The Beaufort Sea ice environment is really comprised of two very different operating areas: nearshore and offshore. Ice cycles and characteristics differ between the two regions, particularly during transitional ice seasons. Since the existing oil exploration and development is concentrated in nearshore areas, there is an immediate need for ice-capable response equipment and systems that utilize smaller vessels and response platforms. If oil development moves further offshore, additional equipment and vessels may be needed to operate in the offshore environment, where larger vessels may operate more effectively but where transitional ice periods may be longer in duration, posing other response challenges.

4.3 Research and Development Needs

4.3.1 INCREASE EMPHASIS ON MECHANICAL RECOVERY

In general, the emphasis among researchers in the oil spill response field who are addressing arctic oil spills seems to be on non-mechanical recovery. At the 2006 AMOP conference, there was not a single paper given on mechanical recovery in ice, while entire sessions were devoted to dispersants and in-situ burning. The ongoing Joint Industry Program (JIP) includes both mechanical and non-mechanical research priorities; however, the project lists for dispersants and in-situ burning are much more specific than the general research priorities for mechanical recovery.

The environmental ministry in Finland also promotes mechanical recovery, and the vast majority of products on the market today are produced by the Finnish manufacturer Lamor. By comparison, the U.S. government and U.S. equipment manufacturers have been far less active in mechanical recovery R&D. It is important that agencies such as ADEC, who favor mechanical recovery over chemical countermeasures, continue to advocate for research and development

into new technologies. Other U.S. agencies and funding sources should also acknowledge this need and promote additional study of mechanical recovery technologies. Partnerships between ADEC, academic institutions, and practical researchers (such as the CRREL facility staff) could also be explored as a possible avenue for enhancing U.S. research and development into new mechanical recovery technologies for the Beaufort Sea.

4.3.2 TEST NOVEL SKIMMING CONCEPT IN BEAUFORT SEA FIELD TRIALS

Early tests of the novel skimmer surfaces in open water (at Ohmsett) showed that, by tailoring the skimmer surface to the oil properties, recovery could be enhanced by as much as 50%. Recent tank tests in slush ice show that the grooved drum skimmers can operate effectively up to 30% ice. ADEC observed those tank tests, and should continue to monitor trials of these novel surface skimmers. Field trials and tests in additional ice conditions will add to the information available about these skimmers.

4.3.3 CATEGORIZE AND RATE RESPONSE EQUIPMENT FOR USE IN BROKEN ICE

While the "World Catalog of Oil Spill Response Products" considers broken ice as one of several possible operating environments, this categorization is not followed through in the analysis and rating of equipment. For example, skimmers and boom are categorized in the Catalog as either open water or protected water. A similar consideration should be given for the broken ice environment, or the specifications and discussion should be expanded to summarize data from tank and field trials in sea ice. Where possible, the maximum operating limits should be expressed in terms of percent ice coverage, maximum size ice piece, and other qualifications (e.g., grease and frazil ice).

Appendix A: Oil and Ice Interactions

A.1 Formation and Characteristics of Sea Ice

Sea ice is characterized by its variability based on air and water temperature, salinity, tides and currents, precipitation, and water depth (AMAP 1998). Although always in transition from one form to another due to seasonal and diurnal changes in temperature, weather, and tide, it is useful to look at the basic forms of ice in high latitude marine environments to better understand how they may affect oil spill response. Numerous terms have been developed for different forms of ice and snow; those listed here reflect the general terminology used in oil spill response literature, and are based on a glossary of sea ice terminology from the World Meteorological Organization (WMO).

A.1.1 FAST ICE

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

A.1.2 DRIFT ICE

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

- **Pack ice** describes any concentrated ice cover that is not attached to land and exceeds *60-70% coverage* (WMO 2005, Dickins and Buist 1999). Pack ice may range from less than one metre to many metres thick. This ice typically moves with the water current.
- **Dynamic drift ice**, which is sometimes referred to as "broken ice" may exist in the transition phases of freeze-up or break-up, persist throughout the winter in areas that do not reach full pack ice coverage, or exist at the edge of pack ice in the marginal ice zone (MIZ) (Økland 2000). Dynamic drift ice includes brash or slush ice as well as larger ice floes that move with the water current and wind. Irregular floes, often with "grease" ice or slush on the water's surface in between them, are impacted by wind and wave action, which may be greater closer to open water (Dickins 2005). Dynamic drift ice can be considered to be a collection of chunks of ice *up to 60-70% coverage* (above this would be pack ice,). Dynamic drift ice includes pancakes, ice cakes, and floes, all

terms referring to different sized pieces of floating ice. In the spring melt, the chunks of ice may become "rotten" and honeycombed as the ice disintegrates.

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

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

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

A.1.3 ICE DEVELOPMENT

Though some ice may persist through the summer melt (known as multi-year ice), the development of first year ice follows the simplified process outlined in Figure A-1. During freeze-up, the water surface may be covered with a thin slurry of ice, or a thicker slushy layer (Dickins 2005). As this ice solidifies into ice pancakes and then floes, a dynamic drift ice field is formed (Wilson and Mackay 1987). It may solidify fully into a pack ice formation, or remain as chunks of drifting ice. The process is not necessarily linear (some stages may not happen), and the amount of time each stage takes will vary considerably. The actual ice development process depends on a wide range of factors specific to any one location, including sea state.

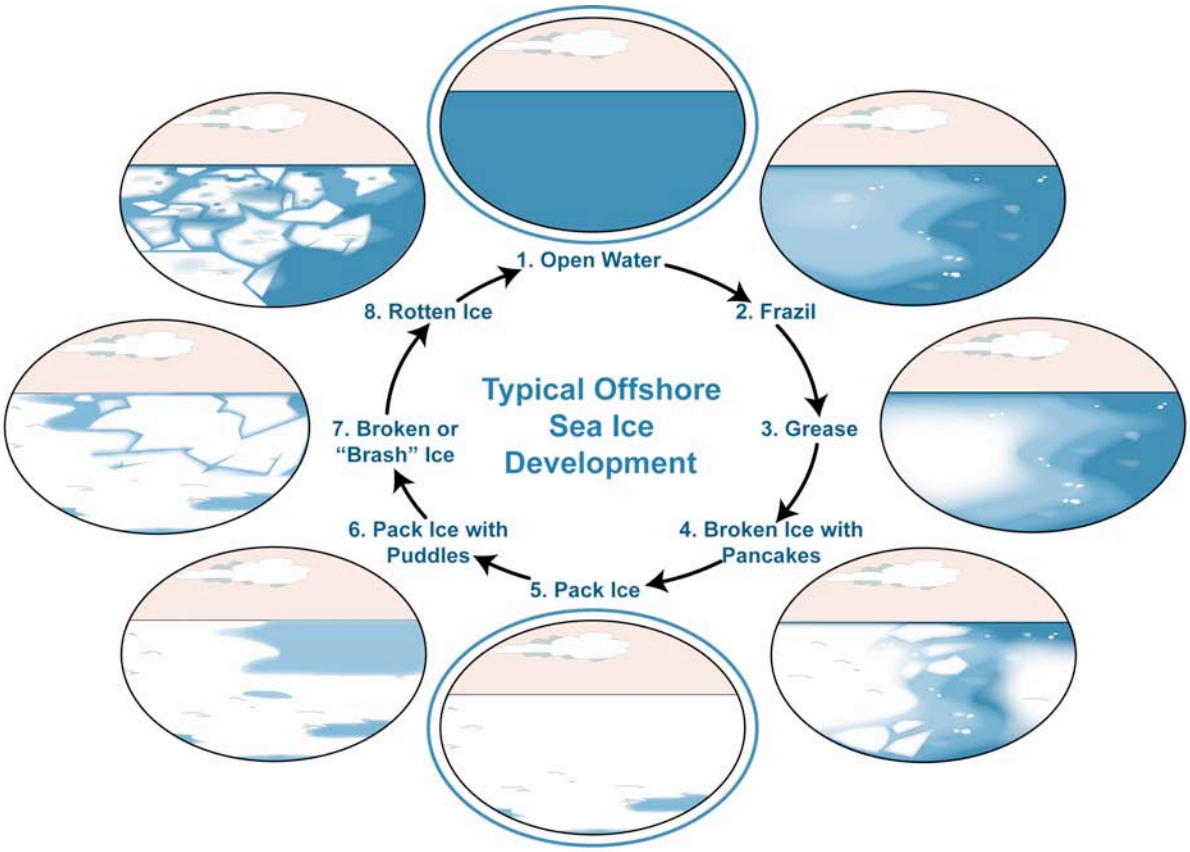
A.1.4 STRUCTURAL VARIATIONS

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

- **Polynyas** are caused by offshore wind conditions or warm water upwelling and are biologically rich areas with high rates of phytoplankton production. Polynyas are variable features, and may open and close depending on conditions (AMAP 1998).

- **Leads** are openings in ice that are navigable by a vessel (WMO 2005). These, too, are variable. Leads may also be created using ice-breaking or ice management vessels.

Figure A- 1. Typical offshore sea ice development.



A.2 Behavior of Oil in Ice Conditions

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

Factors influencing the behavior of oil in ice conditions fall into several categories, described in Table A-1. The nature of the ice tends to dominate other factors in impacting the behavior of oil after a spill (Evers *et al*. 2004). Ice coverage below 30% is not believed to significantly impact oil behavior (Dickins and Buist 1999),

although it has been observed to impact oil spill recovery activities (IT Alaska 2000, Robertson and DeCola 2001). Typically, 30% ice coverage or greater will significantly impact the behavior of spilled oil (NRC 2003b).

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

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

Table A- 1. Factors influencing the movement of oil in ice conditions.

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

A.2.1 IMPACT OF COLD AND ICE ON TYPICAL OIL WEATHERING

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

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

If the type of oil and the presence of waves lead to emulsification, the volume of the oil-water mixture will increase the size of the slick and other weathering processes will slow (NRC 2003b).

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

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

A.2.2 IMPACT OF ICE STRUCTURE ON OIL BEHAVIOR

The presence of ice can impact oil behavior by trapping the oil, controlling the rate of spread, and making it difficult to track. Observations from actual spills, laboratory experiments, and field studies provide some insight into the ways oil can interact with different ice formations. The oil and ice interaction is heavily influenced by whether the oil is released above or below the ice.

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

The actual behavior of oil spilled to grease or brash ice has been widely variable. Oil has been trapped at the edges of ice pancakes, frozen in place, caught within the structure of the grease ice, observed moving under the ice and dispersing as leads open, and carried underneath brash ice (Fingas and Hollebone 2003). Thus, it is extremely difficult to predict the movement of oil in this dynamic context.

Oil released under fast or pack ice will not spread as evenly as it might on the water surface. The rough underside of the ice will cause the oil to pool in some places, unless the current is strong enough to keep the oil moving (AMAP 1998). Late-winter ice tends to be rougher in texture and therefore able to hold more oil pooling under its uneven surface. It is estimated that 1.5 million liters/km^2 of oil could be stored under late winter fast ice along the Alaska North Slope (Dickins and Buist 1999).

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

Oil trapped under multi-year ice could remain in the marine environment for many years (AMAP 1998) and may not be released until it slowly migrates to the surface. Some scientists estimate oil could be trapped under multi-year ice for up to a decade (NRC 2003b).

Oil spilled on the surface of an ice sheet tends to pool in ice depressions, and may be trapped under snow cover. However, oil spilled on top of the ice surface will be exposed to the air and subject to evaporation (Owens *et al.* 2005).

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

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

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

Bacteria and some fungi will slowly degrade petroleum hydrocarbons spilled in the marine environment (AMAP 1998); however, degradation is slower in cold water areas than in temperate regions because the oil tends to be more viscous and not evaporate as quickly, making it less accessible to bacteria. (Atlas 1985 in AMAP 1998).

The behavior of oil in different types of ice is summarized in Table A-3.

Table A- 3. Behavior of oil spilled to different types of ice environments (NRC 2003b).

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

A.2.3 IMPACT OF ICE SEASON ON OIL BEHAVIOR

Oil behavior in ice is heavily influenced by the season in which it is spilled. Oil spilled on fast or pack ice during fall freeze-up will likely migrate downwards as the ice develops and remain encapsulated, moving with the ice pack until the spring melt. Figure A-2 illustrates the interaction between spilled oil and a variety of ice configurations.

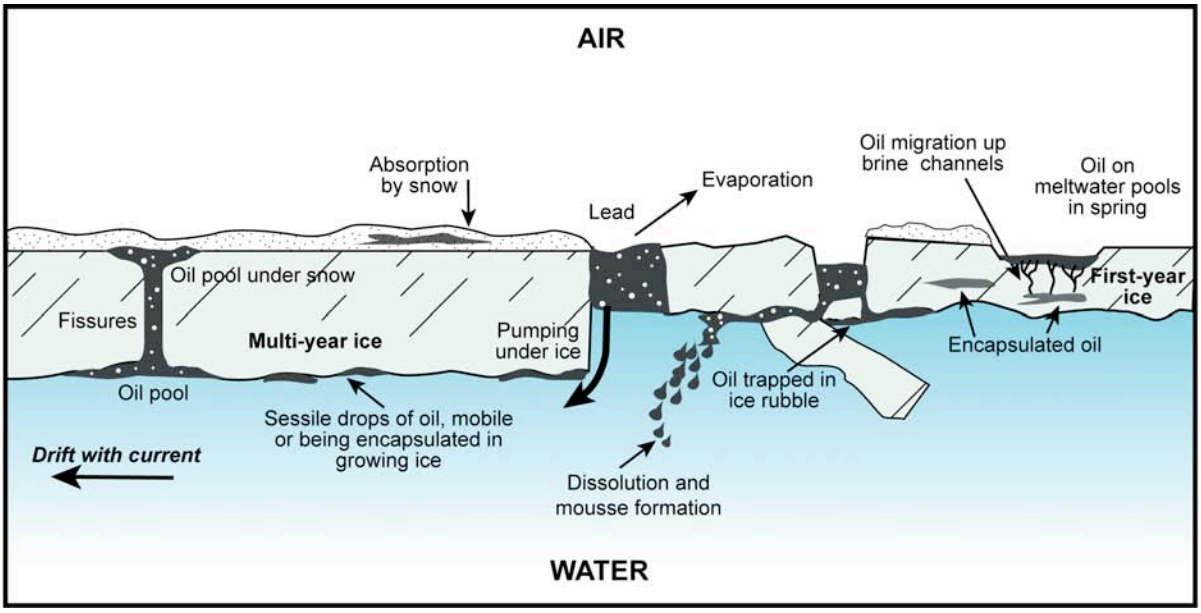
If oil is spilled in dynamic drift ice during fall freeze-up, it will become part of the ice floes as grease ice solidifies into pancake ice, and continues to build into solid ice formations. A rapid freeze can cause this to happen quickly, making oil recovery operations futile (Metge in Wilson and Mackay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

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

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

weathered oil. Fine droplets of oil, such as the spray released from an oil well blowout, may take more time to reach the surface than a thicker slick (Dickins and Buist 1999).

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



Appendix B: Overview of Mechanical Oil Spill Recovery Technologies and Systems used in Ice-infested Waters

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

For the purpose of this report and analysis, mechanical oil spill recovery technologies that may be used in ice-infested waters are divided into six categories:

- Containment
- Recovery
- Ice processing
- Ice management
- Pumps and pumping systems

This appendix describes the technologies and tactics that have been developed for each category, and considers the potential challenges in applying each to spill response in the nearshore and offshore Beaufort Sea.

B.1 Containment

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

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

- Fence booms
- Curtain Booms – which are categorized according to their flotation:

  - Internal foam
  - External foam
  - Self-inflatable
  - Pressure-inflatable
- External tension booms
- Tidal seal booms

Containment booms used in ice-infested waters are generally the same or modified versions of containment booms used for open water recovery. The presence of sea ice can impact containment boom by causing the boom to tear or part, raising the boom above the waterline so that it does not function as intended, or complicating the deployment process due to navigational hazards.

According to the World Oil and ASTM classifications, containment boom can be classified according to the environment in which it is intended for use: open water, protected water, and calm water. Since there is no separate category for booms used in ice-infested waters, boom models from open and protected water categories will be considered for use in the Beaufort Sea. While calm water conditions may exist in some nearshore areas in the Beaufort at some times, calm water boom is generally not sufficiently durable for deployment when sea ice is present. Table 2 provides specifications for open water and protected water boom.

Table B- 1. Selection of Booms according to water body classification (Potter, 2004 and ASTM, 2003).

Boom Type	Total Height	Minimum Reserve Buoyancy to Weight Ratio	Minimum Total Tensile Strength	Minimum Skirt Fabric Tensile Strength	Minimum Skirt Tear Strength
				(2TM = 2 tension members; 1TM =1 tension member)	
Open water	≥ 36 in.	7:1	10,000 lbs.	2TM – 400 lbs. 1TM – 400 lbs.	100 lbs.
Protected water	18 to 42 in.	3:1	5,000 lbs.	2TM – 300 lbs. 1TM – 400 lbs.	100 lbs.

Boom may be held in place by anchors, vessels, or specialized boom positioning devices such as trolleys. A combination of methods may be used to position boom. Boom that is held in place by static objects, such as anchors, is considered **fixed.** Booming strategies that require ongoing maneuvers to position the boom are considered **live.**

Containment booming can be either a fixed-booming tactic where boom is positioned around the spill source, or live where boom is configured in various shapes to contain oil. In both cases, the purpose of containment booming is to prevent spreading and concentrate the oil for removal with a skimmer. Live containment boom configurations include U-boom (Figure B-1), V-boom (Figure B-2) or J-boom (Figure B-3).

Figure B- 1. U-boom configuration.

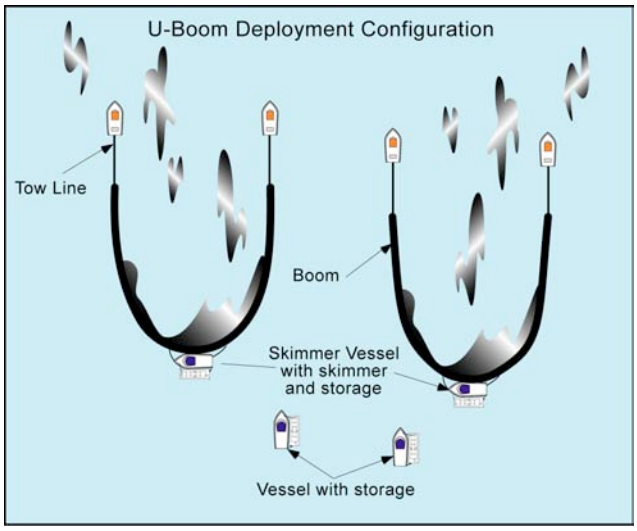


Figure B- 2. V-boom configuration.

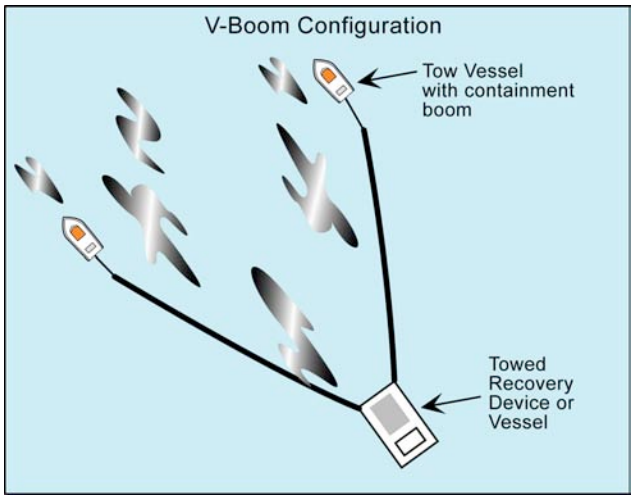
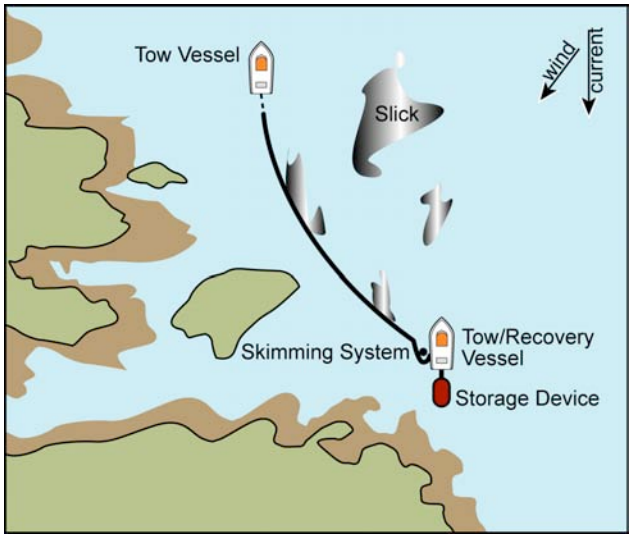
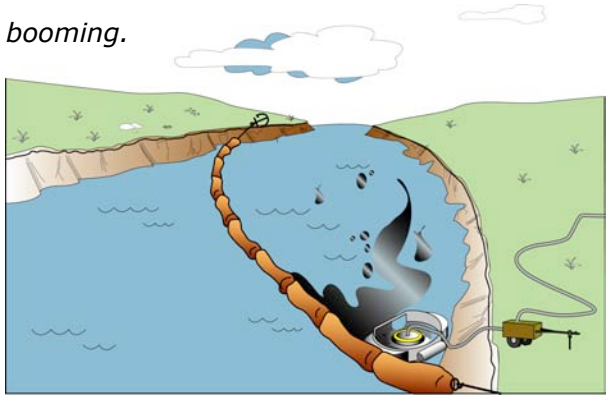


Figure B- 3. J-boom configuration.



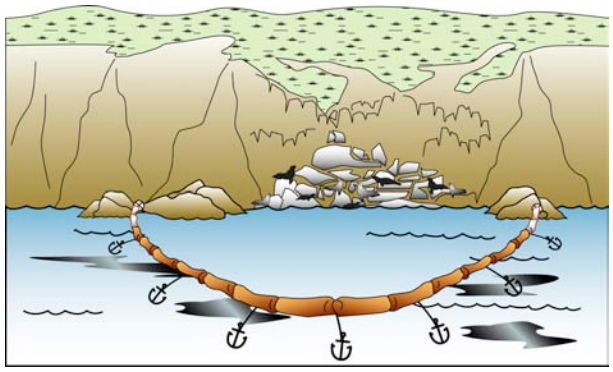
Diversion booming redirects oil to a specific location for recovery. Diversion booming is usually associated with water bodies where currents, winds, or other forces create a directional flow of oil (Figure B-4).

Figure B- 4. Diversion booming.



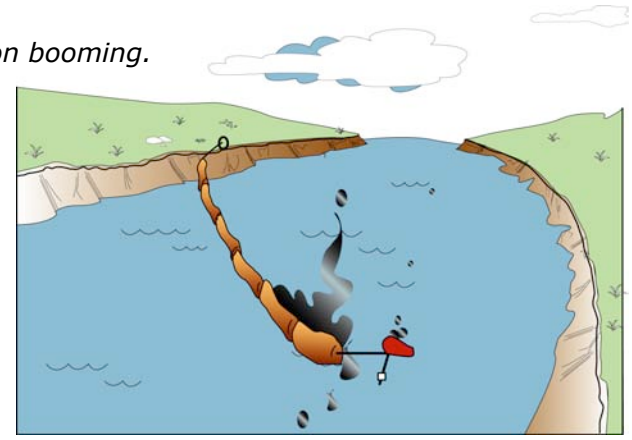
Exclusion booming may be used to prevent oil from entering a sensitive area. Exclusion booming is not necessarily associated with oil recovery, although oil that is excluded may be collected and concentrated for recovery using containment or diversion booming (Figure B-5).

Figure B- 5. Exclusion booming.



Deflection booming is used to direct oil away from a location or to change the course of an oil slick. It is differentiated from diversion booming because in deflection booming, oil recovery is not attempted (Figure B-6).

Figure B- 6. Deflection booming.



B.1.1 IMPACT OF ICE CONDITIONS

The major challenge to containment of oil spills in sea ice is the impact of ice floes and ice pieces on the boom. Booms manufacturer from fabric with a high tensile strength and strong tensile members will perform better when impacted by floating ice. All oil booms will eventually fail once sea ice reaches a certain concentration, due to the strain of the ice on the boom causing the boom to tear or the force of the ice lifting the boom from the water surface. As with most oil spill response technologies, the growing ice cover and grease ice common during freeze-up are more challenging for most oil booms.

B.1.2 DEPLOYMENT CONSIDERATIONS FOR NEARSHORE AND OFFSHORE BEAUFORT SEA

Booming strategies with shoreline anchors (e.g., diversion, exclusion, deflection) will require deployment in nearshore areas, which in the Beaufort Sea may be extremely shallow. U-boom, J-boom, and V-boom configurations may also be deployed nearshore. Vessels used to deploy boom in shallow nearshore areas must be capable of working at shallow water depths, while also having the capability to deploy the boom size and length needed to accomplish the tactic.

For offshore booming, vessels must have the capability to position longer lengths of heavier boom. For both nearshore and offshore deployment, vessels must also be capable of safely operating in the highest possible ice concentration that may be encountered either at the containment site or in transit to or from the site. Vessels used to deploy containment boom either nearshore or offshore must be either kept in an area that remains ice-free throughout the ice season or removed from the water so that they can be accessed for immediate deployment.

B.2 Recovery

Recovery of oil contained or concentrated with boom or natural barriers is accomplished using a skimming or recovery system that removes oil from the surface and transfers the recovered liquids to primary storage. Recovery operations may also involve separating water from the recovered fluids. Like booms, there are many models of skimmers, but all fall into one of three categories.

- **Weir skimmers** draw liquid from the surface by creating a sump in the water into which oil and water pour. The captured liquid is pumped from the sump to storage (Figure 10). Weir skimmers may have either integral or external pumps. Some weir skimmers use mechanical or hydrodynamic force or external water jets to draw oil to and over the weir. Advancing weir skimmers use the forward motion of the system to provide the flow into the skimmer. (Figure B-7)
- **Oleophilic skimmers** pick up oil adhered to a collection surface, leaving most of the water behind. The oil is then scraped from the collection surface and pumped to a storage device. The collection surfaces in oleophilic skimming systems include rotating disks, brushes and drums, or continuous belts or ropes (Figure B-8). Oleophilic skimmers may be configured in a number of different ways:

- **Boom skimmers** are incorporated into the face of a containment boom. They can be any type of skimmer, and may involve one or more skimmers.
- **Brush skimmers** are oleophilic skimmers that use the bristles of a brush to pick up oil. There are 2 main configurations for brush skimmers, based on the surface upon which the bristles are mounted: drum brush and chain brush. Brush skimmers are used most often in the advancing mode.
- **Disc skimmers** are oleophilic skimmers designed to collect oil on the surface of discs rotated through the oil/water interface. Most disc skimmers are stationary, but some may be used in stationary/advancing mode.
- **Drum skimmers** are oleophilic skimmers designed so that oil adheres to the circle of a cylindrical drum for recovery. Drum skimmers are usually stationary but may be used on a dedicated vessel as an advancing skimmer.
- **Belt skimmers** use an oleophilic or paddle belt, which is positioned at an angle to the water and then rotated throught the oil/water interface. Belt skimmers may be used in stationary or advancing mode, depending upon the configuration.
- **Rope mop skimmers** use long, continuous loops of oleophilic material that moves through the oil/water. A roller or wringer removes the adsorbed oil from the rope. Rope mop skimmers are most commonly used in stationary mode where the rope is guided over the oiled water by one or more pulleys.
- **Submersion plane skimmers** use an angled plane to submerge oil and water and then direct the more buoyant oil toward a collection well. Submersion plane skimmers can be fixed or moving and may operate in stationary or advancing modes.

- **Suction skimmers** use a vacuum to lift oil from the surface of the water. These skimmers require a vacuum pump or air conveyor system. Like weir skimmers, suction skimmers may also collect large amounts of water if not properly operated. Most suction skimmers are truck mounted and work best on land. However, suction skimmers for the marine environment have been made by converting fish pumps to oil recovery purposes, or loading a vacuum truck on a vessel (Figure B-9).

Skimmers are also classified according to their mode of application:

- **Stationary skimmers** are always used in a fixed location.
- **Advancing skimmers** must have forward movement for the oil to flow into the system.

- **Self-propelled skimmers** are advancing skimmers that operate within an independently-powered skimming vessel.
- **Stationary/advancing skimmers** are generally used in the stationary mode but may also be used in a slowly advancing system or a system that advances to collect oil then pauses to skim.

Figure B- 7. Weir Skimmers.

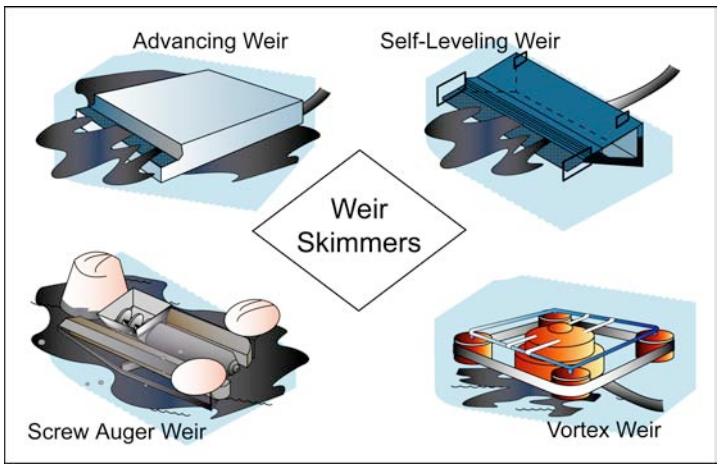


Figure B- 8. Oleophilic Skimmers.

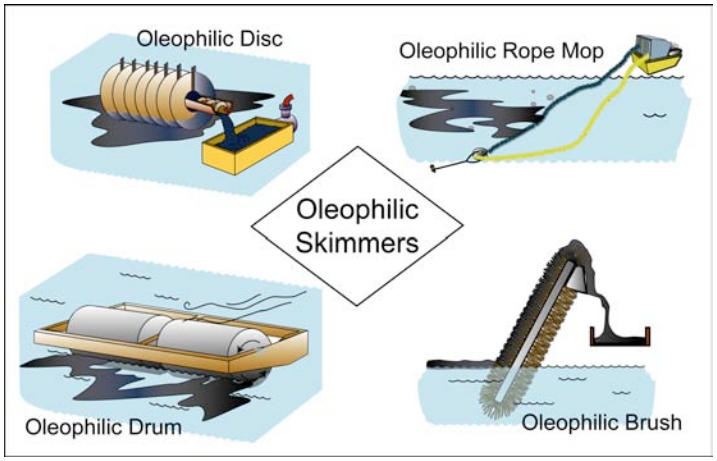


Figure B- 9. Suction Skimmers.

B.2.1 IMPACT OF ICE CONDITIONS

Sea ice can affect skimming efficiencies in a number of ways. It can clog entrances to skimming reservoirs on weir, brush, and suction skimmers defeating their encounter rate. Ice can freeze on brush, disk, and rope mop skimmers defeating their ability to collect oil. Skimmer capabilities diminish quickly in the presence of sea ice. Ice conditions can also preclude the operation of the response vessels that act as operating platforms for the skimmers. In newly forming ice, concentrations as low as 1% have been shown to effectively clog some skimmers. (DeCola and Robertson, 2001) In late season break-up conditions skimmers have been impaired at about 10% ice coverage. Like boom, skimmers function slightly better during break-up conditions than during freeze-up.

Recovery of oil in ice-infested waters presents an additional challenge due to potential interference of ice with the skimmer operations, and difficulties in deploying and operating skimmers from vessels when sea ice is present.

Oleophilic skimmers tend to operate with less sensitivity to debris than weir or suction skimmers, therefore they are often favored for use in sea ice. Suction skimmers can handle ice and debris only up to the size of the transfer hoses or the size the pump can handle. Weir skimmers are more vulnerable to debris, although weir skimmers that use an integral Archimedes screw pump can process more ice or debris than a regular weir.

Brush skimmers are generally tolerant of small debris and may be appropriate for use in lower ice concentrations. With disc and drum skimmers, ice and debris must be managed to allow oil to flow to the skimmer. Belt skimmers tolerate ice and debris relatively well up to a certain concentration or ice size. Rope mop skimmers are also fairly tolerant of ice and debris. Moving submerged plane skimmers can operate among some debris or ice, assuming the ice is managed away from the skimmer inlet. Fixed submersion planes are less tolerant of debris. Some weir skimmers tolerate small debris and ice, although the debris must be managed away from the skimmer head.

B.2.2 DEPLOYMENT CONSIDERATIONS FOR NEARSHORE AND OFFSHORE BEAUFORT SEA

Deployment of skimmers in nearshore areas may occur from a fixed location (landfast ice, dock, shoreline, or other structure) or from a work boat or barge. Vessels used to deploy skimmers in nearshore areas must meet several minimum criteria:

- They must be able to operate safely in the shallowest water depths that may be encountered.
- They must be able to operate safely at the highest ice concentration that may be encountered, both in the recovery area and in transit to and from the recovery area.
- They must be able to operate in the highest sea states and winds that may be encountered, both in the recovery area and in transit.

- They must have sufficient deck space to transport the skimmer to the recovery area.
- They must have the capability to lift and position the skimmer at the desired location within the recovery area, and to move the skimmer if needed.
- There must be some form of primary storage, either on the vessel or towed by the vessel.
- The vessel and crew must be appropriately trained and licensed for the intended operation.

Vessels deployed for offshore operation must also meet all of the criteria above, except for the first. However, for offshore deployment, vessels must be able to operate in higher sea states. Vessels that are intended for use as platforms for either nearshore or offshore recovery during winter ice season must be either kept in an area that remains ice-free throughout the ice season or removed from the water so that they can be accessed for immediate deployment.

B.3 Ice Processing

Ice processing systems, also referred to as oil deflection, have been developed specifically to address the challenges of separating oil from ice to facilitate mechanical recovery. Ice processing systems use technologies such as air jet blowers, propeller wash, pneumatic diversion booms, or vibrating belts or plates to redirect the flow of oil into a collection area while moving ice in a different direction (Dickins, 2004).

Ice processing systems and technologies include market-available oil-ice separators as well as a number of experimental concepts that are in various stages of development and testing.

B.3.1 IMPACT OF ICE CONDITIONS

Since ice processing systems are specifically designed for operation in and among sea ice, their capability in a range of sea ice conditions should be known. There will likely still be an upper limit to the operability of these systems in the presence of sea ice, which should be considered on a case-by-case basis. Since ice processing systems are often used in combination with other mechanical recovery methods (e.g. skimmers), the upper operating limits of other technologies may be the defining limit.

B.3.2 DEPLOYMENT CONSIDERATIONS FOR NEARSHORE AND OFFSHORE BEAUFORT SEA

Ice processing systems have been developed for a range of operating environments. For vessel-based systems, the same considerations apply as discussed for recovery systems in Section B.2.2.

B.4 Ice Management

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

Ice management systems can be as simple as a grate used to prevent ice chunks from entering an area where recovery operations are taking place. A challenge in implementing ice management systems in general, and specifically with deflection devices, is to ensure that oil is not deflected along with the ice. Ice processing technologies may be integrated with ice management to address this challenge.

B.4.1 IMPACT OF ICE CONDITIONS

Like all mechanical recovery methods, there will be an upper limit for the ice conditions in which the ice management technology can be applied. This may be caused because the ice management technique cannot be safely accomplished above a certain ice concentration (e.g. if ice boom or anchoring system fails). The upper limit may also be realized if the ice management system is not wholly effective – e.g. if the ice management cannot reduce the ice concentration down to a low enough level to allow other components of the recovery system, such as skimmers, to function.

B.4.2 DEPLOYMENT CONSIDERATIONS FOR NEARSHORE AND OFFSHORE ENVIRONMENTS

Depending upon their configuration, ice management systems that rely on vessels for deployment must address the same considerations in nearshore and offshore environments as described for containment systems in Section B.1.2 and/or recovery systems in Section B.2.2.

B.5 Pumps and Pumping Systems

Pumps are used to transfer recovered oil and oil/water mixtures during mechanical recovery operations. Pumps are often used to transfer recovered fluids from the skimmer, and also to pump recovered fluids from primary storage to secondary storage. A variety of pumping systems are available for spill response operations, based on the particular requirements of the task. These include:

- **Centrifugal pumps** which use spinning impeller vanes to increase the velocity of the fluid as it moves from the center of the pump to the outer edge. These pumps have high capacities for moving low viscosity fluids. Output decreases rapidly with increases in viscosity.
- **Diaphragm pumps** use a diaphragm to create a pulsating flow. They can handle a wide range of fluids reasonably well.
- **Gear/lobe pumps** force fluids through the pump between intermeshing gears or lobes. They have good suction and are able to pump very viscous fluids but cannot tolerate abrasive debris.
- **Hose/peristaltic pumps** function by alternately compressing and relaxing a specially-designed resilient hose between the inner wall of the housing and the compression shores on the rotor. They are capable of handling fluids of all viscosities but cannot tolerate debris well.
- **Piston pumps** draw suction with a moving piston that creates a positive displacement of fluids. They are able to pump a wide range of fluids at a high output rate, but they cannot tolerate debris well.
- **Progressive cavity pumps** are usually a single-screw rotary pump in which a spiral rotor turns eccentrically in an internal-helix stator to form pockets of fluid that are continuously pushed along the stator to an outlet. They can generally handle low-to-medium viscosity fluids.
- **Archimedean screw pumps** use mechanical lifting properties to move highly viscous materials. They offer very little suction compared to other pumps; however, they are able to move highly viscous liquids and can tolerate debris fairly well.
- **Vane pumps** contain a rotating cavity that fills with fluing that is moved by the rotation of a central shaft. They are suited to a wide range of viscosities but are damaged by debris or abrasives.
- **Vacuum systems** use a vacuum to bring fluids through the hoses. The size of debris they can tolerate is usually dictated by the size of the hoses.

B.5.1 IMPACT OF ICE CONDITIONS

When sea ice is present, recovered oil may include small ice pieces or slush ice, which can disable some types of pumps. Cold temperatures also increase oil viscosity, which can make pumping more challenging. In considering pumps for use in pumping viscous oils, the strength of gaskets, connectors, and other hose fittings must also be capable of withstanding the pressure that develop. The pump must also be capable of processing ice and other debris. All pumps will have an upper limit for ice concentration, above which they may not function effectively or at all.

In general, centrifugal pumps can tolerate only small pieces of ice or debris, in low concentrations. Since they are not very effective with high viscosity oils, they are generally not appropriate for use in cold conditions. Piston pumps are generally unable to handle debris. Progressive cavity pumps, gear/lobe/screw pumps, and vane pumps all have limited debris tolerance as well. Archimedean screw pumps have been proven to handle ice and debris better than other pump types during on-water recovery operations. Vacuum pumps also have a high debris tolerance; however, they are generally not used in marine recovery.

B.5.2 CONSIDERATIONS FOR NEARSHORE AND OFFSHORE ENVIRONMENTS

Pumps used in arctic environments are subject to freezing and must be built such that thawing and repairs can be easily accomplished. Pumps must be portable and have a ready power supply. Power supplies independent of the vessel's power are preferred. Pumps that are used as components of an on-water recovery system are subject to the same vessel deployment considerations in nearshore and offshore environments as described for recovery technologies in Section B.2.2.

Appendix C: Acronyms and Abbreviations

AAC	Alaska Administrative Code
ACS	Alaska Clean Seas
ADEC	Alaska Department of Environmental Conservation
AMAP	Arctic Marine Assessment Program
ASTM	American Society for Testing and Materials
BAT	Best available technology
BPXA	British Petroleum Exploration Alaska
CRREL	Cold Regions Research Engineering Lab
DBD	Desmi brush drum
DOP	Displacement oil pump
EP	Expanded polystyrene
FOB	Foam-filled oil boom
GT/GTA	Lamor pump model type (not acronym)
HDB	Heavy-duty boom
ILB	Inflatable light boom
JIP	Joint industry program
LAS	Lamor Arctic Skimmer
LIC	Lori/Lamor Ice Cleaner
LOIS	Lori/Lamor Oil-Ice Separator
LRB	Lamor Recovery Bucket
LSC	Lamor Side Cleaner
MIZ	Marginal ice zone
MMS	Minerals Management Service
MORICE	Mechanical Oil Recovery in Ice-infested Waters
NRC	National Research Council

OSRI	Oil Spill Recovery Institute
RMROL	Realistic maximum response operating limitation
SINTEF	The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology
STAR	Spill Tactics for Alaska Responders
SYKE	Finnish Environment Institute
TM	Tension member
UCSB	University of California at Santa Barbara
VTT	Finnish Environmental Institute
WMO	World Meteorological Organization

Appendix D: References

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