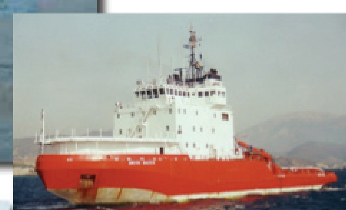
Shell's Beaufort Sea Exploratory Drilling Program
Oil Spill Response in Ice







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Prepared for:

Shell Exploration and Production Co.

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Prepared By:

David F. Dickins
DF Dickins Associates Ltd.
info@dfdickin.com

Alan A. Allen
Spiltec
allan@spiltec.com

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SUMMARY

This paper addresses Shell's exploration program in the Alaskan Beaufort Sea, focusing on how Shell will carry out its mission to protect the Arctic environment and to be fully prepared should an oil spill occur. The focus of the technical discussion is on describing effective strategies to achieve high volume removal rates where ice precludes an effective Tier 3 Worst Case Discharge (WCD) response based solely on mechanical recovery systems. Under the U.S. Incident Command System (ICS) approach to emergency management, spill plans are organized according to a tiered response system progressing from Tier 1 (small-locally significant) to Tier 2 (medium – regionally significant) and finally to the focus of this report, Tier 3 (large-nationally significant).

The scope of this document is limited to discussing the technical, planning and operational aspects of implementing specific offshore recovery and removal strategies where ice plays a major role in dictating the appropriate choice of effective tactics. Numerous other important response topics are more fully described within Shell's Regional Exploration Oil Discharge Prevention and Contingency Plan (hereafter known as the c-Plan) submitted to the Minerals Management Service in January 2007, for example: community and agency notification, environmental impact assessment, wildlife rescue and rehabilitation, shoreline protection, communications, reporting and spill management systems.

Program Overview

Shell's offshore drilling program, beginning during the summer of 2007, will involve two floating drilling systems, supported by 16 vessels (including four polar icebreakers), for the provision of fuel and supplies, anchor-handling, personnel and equipment transport, ice management, and oil spill response including the storage of recovered products. The offshore activities will occur, over approximately four months from July to October, in water depths of about 100 feet, approximately 15 miles offshore (see Figure 1 following). The drilling program will begin after the nearshore fast ice has broken up and proceed in predominantly open water conditions from mid-August on. However, because of the possibility of ice incursions during the open water period and the natural variability of the timing and duration of freeze-up, the oil spill response strategies and tactics are designed to cover a wide range of open-water and ice conditions (see examples illustrated below).

Planning and Resources

Based on previous exploration programs in the Chukchi and Beaufort Sea regions, Shell has the experience of meeting the challenges of drilling under extreme Arctic conditions many miles from populated centers and other support facilities. This background is fully utilized in meeting the overriding goals of the 2007 c-Plan to: prevent oil spills, protect the environment and work with local communities to understand and preserve their cultural needs. Proper planning, selection of advanced ice-capable vessels and equipment, continual training on location and reliance upon local knowledge are the keys to creating a world-class, safe and reliable oil spill prevention and control program for the Beaufort Sea.

Examples illustrating a number of Arctic spill response strategies covered in this document: detection and tracking, on-ice operations, burning, mechanical recovery and ice management.

Photos: Sakhalin Energy/Aker Arctic/SINTEF/Lamor/DF Dickins

Along with the commitment to prevent all spills and to put the safety of people as the highest of priorities, every effort is made to involve highly qualified personnel at all levels, experienced with the techniques and equipment needed to conduct a safe and effective offshore program. Steps taken by Shell to meet these commitments include:

- A comprehensive Beaufort Sea Regional Exploration Oil Discharge Prevention and Contingency Plan for review and approval by state and federal agencies (Shell 2007).
- A Critical Operations and Curtailment Plan specifying strict procedures to monitor weather and hazardous ice conditions.
- Capable vessels and equipment that can be activated immediately and operate for extended periods in open water and broken-ice conditions to mechanically contain and recover spilled oil or eliminate oil using controlled burning.
- Studies and ongoing field surveys of the marine operating environment (ice, weather and sea conditions) in the Beaufort Sea.
- A comprehensive assessment and continued re-evaluation of countermeasures (mechanical removal, in situ burning, dispersant application and tracking) that are appropriate and reliable in extreme cold climates.
- The identification and preparation of specific response strategies and tactics that could be implemented safely and effectively under a broad range of conditions including: drifting floes at break-up, open water, summer-ice incursions and new ice at freeze-up.

Operating Environment

Shell and its response contractors are well aware that while traditional containment and recovery operations can be used effectively during the open-water period, the greatest challenges involve the presence of ice at the end of break-up early in August, during periods of summer-pack ice incursions and during the early stages of freeze-up in late October (compounded at that time by cold temperatures and rapidly diminishing daylight). Response tactics need to be selected with a full awareness of the constraints imposed by often unpredictable and dynamic environmental conditions. The Operating Environment section summarizes the wind and sea conditions, types and amount of ice, visibility, etc. that influence the selection of appropriate oil spill response countermeasures.

Response Strategies

Shell's offshore and nearshore spill response plans include dedicated personnel and equipment in a constant state of readiness, drawn from Alaska Clean Seas (ACS), ASRC Energy Services Response Operations, LLC, Consultants, and Shell personnel, supported by an ice-capable marine fleet (examples are illustrated in Figure 2).

Response systems will be maintained ready for immediate deployment with trained personnel from vessels and barges onsite and in close proximity to the drilling rigs. The ice-strengthened vessels and barges will carry high-volume-throughput skimming systems that can recover oil and emulsions at rates that are several times the Worst Case Discharge (WCD) planning standards required by federal and state regulations.

The presence of cold water and ice can enhance response effectiveness by limiting oil spreading and slowing weathering. By working with the natural environment as much as possible (e.g. utilizing and promoting containment of oil by ice), responders often can increase the response window-of-opportunity and improve the effectiveness of mechanical recovery and in situ burning techniques under specific conditions. Deliberate ice management can be used in some situations, for example: To extend the window of operation for booms and skimmers (ice deflection), and to release/expose trapped oil for burning in the case of high-ice concentrations. The ultimate goal is to have access to a broad range of response options that provide the greatest flexibility in being able to deal with rapidly changing offshore environments.

As ice concentrations progress from open-drift to heavier-pack ice conditions, mechanical recovery systems experience progressively lower oil encounter rates as crews shift from large open apex booms to individual over-the-side skimmers to access pockets of oil trapped between ice cakes and floes or in leads. As the effectiveness of mechanical recovery declines in expanding ice coverage, Shell would work closely with the Unified Command (UC) and the Regional Response Team (RRT) to continually assess the potential for controlled burning and at the appropriate time, refocus the primary response effort towards ignition and combustion of oil contained naturally by the ice.

Combustion also may play an important immediate role for safety reasons in the unlikely case of a blowout. Because of the likely release of large quantities of natural gas and vapors from the surfacing oil, it is likely that a decision would be made to ignite the gas as soon as the drilling rig moves off location. This action would eliminate the risk of a dangerous accidental ignition when vessels are in close proximity and could potentially eliminate a significant percentage of the oil.

Because of the importance of controlled burning as a rapid and effective means of eliminating large volumes of oil quickly, with and without ice, considerable discussion is provided in this report about the scientific principles and physical processes involved.

If the oil is properly contained (by fire booms or ice), burning even relatively thin layers only a few millimeters thick can result in removal efficiencies of 50 to 70 percent. Thicker oil layers commonly achieved in booms or wind-herded against ice or a shoreline can easily support removal efficiencies in excess of 90 percent. With burns potentially eliminating on the order of 1,000 barrels of oil per hour over a burn area only 100 feet in diameter, the combustion of oil holds great promise for a spill source that is fixed in location, relatively localized on the sea surface, and comprised of highly flammable, fresh oil. The burn strategies described in this report include careful note of the constraints that also apply to the burning of oil on water: namely that the oil must not be emulsified much beyond 25 percent; and that winds can make ignition difficult if they exceed 20 mph. All burning must be carried out in accordance with key safety issues, including: Being aware of the presence of flammable slicks in close proximity to the controlled burn, ensuring that burning can be sustained without risk to nearby vessels and confirming that the products of combustion (primarily the visible smoke plume) will not impact communities and other sensitive resources downwind.

Controlled in situ burning of oil, especially during extreme operating conditions that seriously reduce the efficiency and/or increase the risks of physical removal, provides a unique response option for cold climates with and without ice present. By working in close consultation with the regulatory agencies and other stakeholders, and by including a careful monitoring program to predict and assess the trajectory of the smoke, the burning of oil can take place with minimal environmental impact. Oil burns can be limited to sites that are a minimum safe distance, generally three or more miles upwind of human populations, and carried out in full compliance with the inter-agency guidelines (ADEC et al. 2007 Rev.).

Conclusions

Shell, together with its highly trained primary response contractors, ASRC Energy Services (AES) Response Operations, LLC and Alaska Clean Seas (ACS), has developed one of the most comprehensive oil spill response programs ever assembled for an Arctic exploration program. In the remote event of a major spill, Shell's response team will be ready, on location, to recover and eliminate as much oil as possible and to minimize environmental impacts.

Conventional open-water recovery systems are capable of dealing with discharge volumes over four times greater than the federally or state mandated WCD in open water (less than 1/10 ice) and potentially at a reduced capacity over a range of open drift conditions (1-6/10) depending on the ice distribution and floe size. In a typical year, these systems are applicable through most of the drilling season from early August to mid-October. In more severe ice concentrations (e.g. drifting floes at break-up, ice incursions in summer and new ice at freeze-up), the recovery effectiveness of mechanical recovery systems (with or without booms) drops sharply to the point where response strategies need to focus on burning to achieve the required oil removal rates.

Controlled burning is a proven Arctic response strategy developed in more than 30 years of experience incorporating extensive lab and tank testing, large-scale field experiments and actual incidents. Established guidelines are in place to allow in situ burning to take place with scientifically monitored safeguards to protect responders, the environment and local populations.

The physical parameters surrounding Shell's spill scenarios (nature of the release and environmental conditions) support the choice of burning as an effective response option in any significant ice cover. Key aspects to this decision include:

- The fresh nature of oil released to the surface;
- Limited oil spreading due to reduced temperatures;
- Slower weathering rates related to thicker films and lower-wave energy;
- A high potential for effective ice containment in any close-pack condition; and
- Moderate sea states associated with any significant ice in the vicinity.

At an operational level, by having vessels and critical resources at or near the drilling locations, responders are able to access the oil quickly and implement the most appropriate response strategy according to conditions at the time. The availability of four highly capable support icebreakers, including the latest generation of vessel with azimuthing drives, provides an opportunity to effectively manage the ice for spill response through such measures as ice deflection, flushing trapped oil from beneath small floes, and breaking down large floes to expose oil for burning or recovery.

Important issues and uncertainties affecting the success of a spill response in ice involve the unpredictable and dynamic nature of the offshore environment, and challenges of operating late in the season with freezing temperatures and darkness. Fortunately, at that time, the ice acts as an effective containment mechanism, minimizing the contaminated area, and maintaining thick oil films for burning through aerial ignition (reducing the exposure of responders on the surface to extreme conditions). In the case of a late-season incident, proven techniques are available to track oiled ice for extended periods and to take advantage of opportunities to access the oil with helicopter-transported crews as the ice develops.

The paper focuses on the following topics:

- Operating Environments;
- Operational Preparedness;
- Spill-Response Countermeasures; and
- Strategies for Burning in Ice.

A companion paper entitled, "Oil Spill Prevention Through Risk Management" discusses how Shell will carry out its mission to prevent spills.

INTRODUCTION

Background and Scope

Shell Exploration & Production Company is preparing for a multi-year, offshore exploration program in the Alaskan Beaufort Sea beginning in the summer of 2007. The exploratory program will be seasonal with operational activities and drilling taking place over a period of approximately four months from July to October, and potentially into November. Figure 1 (page following) shows the proposed drilling locations and marine access routes (Shell 2007).

The exploration program uses a specialized icebreaking conical drilling unit with a long track record of successful Arctic wells drilled and an ice-strengthened state-of-the-art drillship. Four highly capable polar icebreakers will manage the ice in support of the drilling rigs. In addition, an extensive support fleet includes specialized supply and oil spill response vessels and barges, and a dedicated double-hull tanker for offshore storage of any recovered products in the remote possibility that there is any accidental discharge (see selected fleet examples in Figure 2).

Figure 2: Selected photos of Shell's Arctic drilling rigs and ice-capable support vessels.

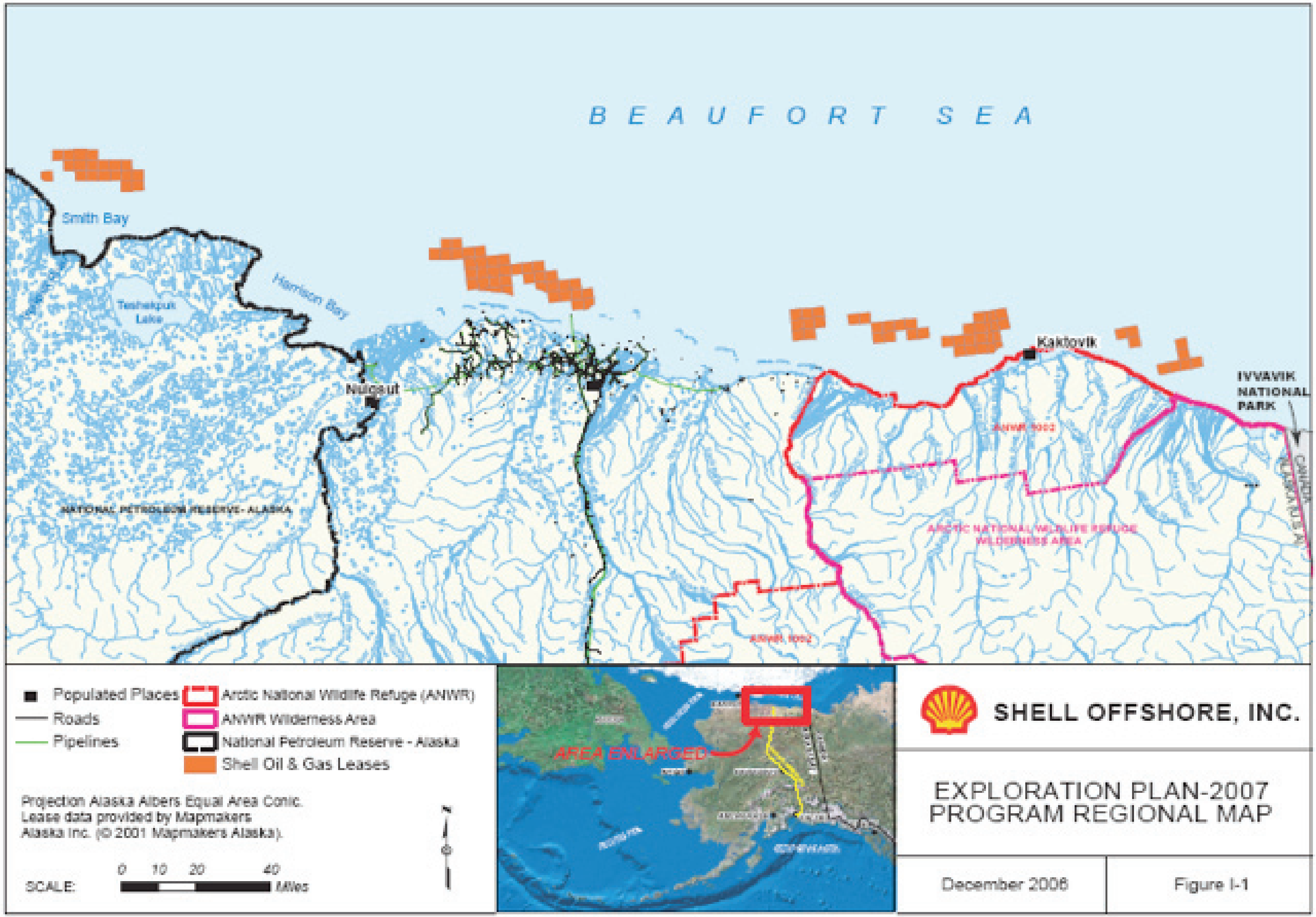


Figure 1: **Location Map**

This paper discusses how Shell will carry out its mission to protect the Arctic environment and be fully prepared should an oil spill occur. The technical discussion focuses on strategies required to achieve high-volume removal rates where ice precludes an effective Tier 3 Worst Case Discharge (WCD) response based solely on mechanical recovery systems. Under the U.S. Incident Command System (ICS) approach to emergency management, spill plans are organized according to a tiered response system progressing from Tier 1 (small-locally significant) to Tier 2 (medium – regionally significant) and finally to the focus of this report, Tier 3 (large-nationally significant).

While traditional containment and recovery operations can be used effectively during the open-water period, the greatest challenges involve the presence of ice and the reduction of daylight hours as summer gives way to freeze-up and early winter conditions. Consequently, the scope of this document is limited to discussing the engineering and operational aspects of implementing specific offshore recovery and removal strategies where ice plays a major role in dictating the appropriate choice of effective tactics. Other important response topics are fully described within Shell's Oil Discharge Contingency Plan submitted to the Minerals Management Service and include (not limited to): Community and agency notification, environmental impact assessment, wildlife rescue and rehabilitation, shoreline protection, communications and reporting and spill management systems.

The following chapters are organized around a series of topics addressing how changing offshore conditions through the drilling season affect the planning and execution of an effective response operation in the Beaufort Sea. These topics include:

- Operating Environments (ice, weather & sea conditions);
- Operational Preparedness (planning, personnel & equipment);
- Response Countermeasures (mechanical removal, burning, dispersants and tracking); and
- Strategies for Burning in Ice (from less than 1/10 concentration to continuous new ice).

A companion paper entitled, "Oil Spill Prevention Through Risk Management" discusses how Shell will carry out its mission to prevent spills.

OPERATING ENVIRONMENT

The marine operating environment affects all aspects of the drilling operation including the selection and outfitting of suitable rigs and vessels, and design of the oil spill response system. Strategies for efficient oil spill response using a combination of mechanical and burning tactics and spill mapping and surveillance, are directly linked to the nature and amount of ice present, winds, waves and visibility. This section provides an overview of important ice, meteorological and ocean conditions in Shell's areas of interest in the Beaufort Sea.

The Ice Environment

Drifting pack ice is present year-round off the Alaskan coast. From late October to June, a vast area from shore out to between 50 and 100 feet of water usually is covered with a continuous sheet known as fast ice. In the "summer" months from July to September, the fast ice is replaced by open water while the pack ice retreats to the north, normally leaving the drilling locations free of ice for several months. The patterns of ice break-up and clearing vary greatly from year to year along with the geographic extent and continuity of the ice-free window.

The geographic reference frame used here to describe the ice environment includes Shell's drilling locations in depths close to 100 feet and the routes connecting those sites with logistics access points, such as Prudhoe Bay/West Dock. There are differences in ice conditions between the different proposed drilling locations shown in Figure 1. For example, sites in the Eastern Beaufort such as Fireclaw, Fosters and Olympia will tend to clear earlier under the influence of expanding open water from the Canadian Beaufort in June and July (Dickins and Oasis, 2006). More central Beaufort locations from Sivuliq to Cornell will experience very similar patterns of break-up and freeze-up and open-water duration.

The following discussion proceeds from an overview of ice zones and timing to descriptions of the changing composition of the ice cover through the drilling season.

Overview of Ice Zones and Timing

Figure 3 shows a segment of a NASA MODIS image acquired May 22, 2002 showing the ice zones off the Alaskan Coast at the end of winter. Major rivers are beginning to flood out onto the nearshore sea ice. The clearly defined fast-ice edge visible in this image typically occurs in water depths out to 95 feet in late winter (Eicken et al., 2006). Offshore ice concentrations are generally eight to 9.5/10 (80 to 95 percent ice coverage) with scattered openings, and separated from the fast ice by a broad open flaw (coast following) lead.

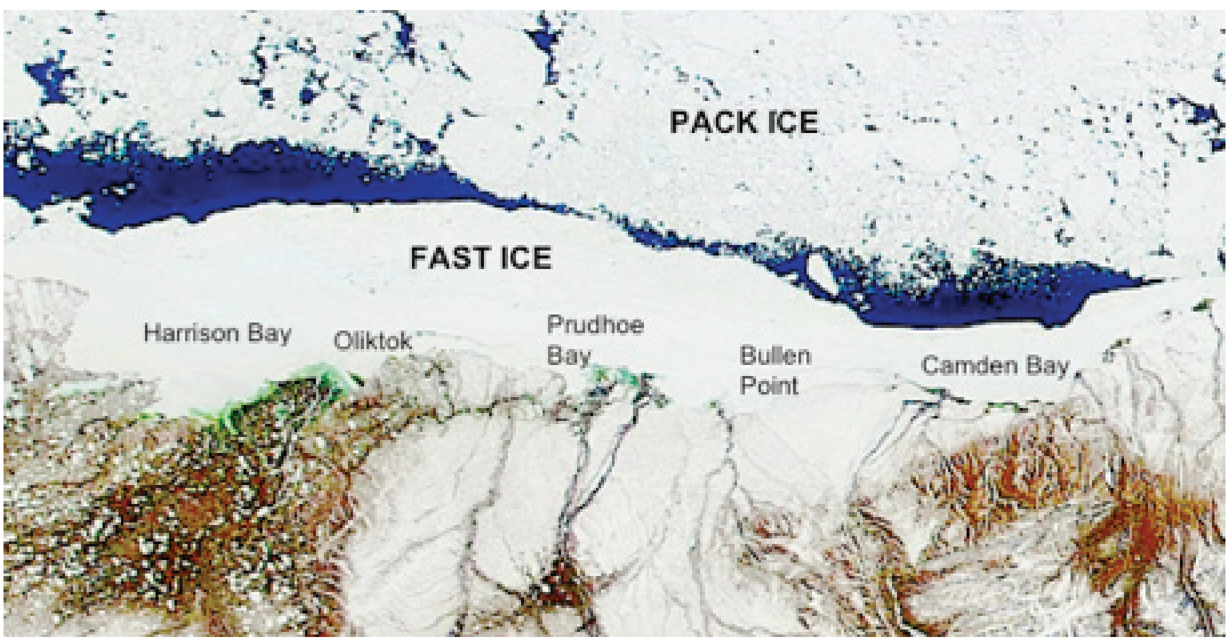


Figure 3: MODIS image showing the different ice regimes on May 22, 2002 (NASA). Note the broad flaw lead encompassing many of the drilling locations shown in Fig. 1.

Figure 4 shows a simplified cross-section of typical ice zones off the Alaskan North Coast:

The three primary ice zones shown in Figure 4 can be further subdivided and defined as follows:

- Fast Ice
    - » Bottom fast area where the ice is in direct contact with the seabed (extending out to 6 feet of water late in the winter).
    - » Floating fast ice anchored at its seaward boundary by a complex zone of partially grounded ridge systems (Shear zone).
- Shear zone (spanning the transition from fast ice to pack ice): This zone often bridges the fast ice and pack ice boundaries. An area of active ridging and rubble formation, the shear zone is highly variable in extent but generally occurs between the 40-45 feet and 80 feet isobaths (also referred to as the Stamukhi zone in Alaskan ice references (Kovacs, 1996; Reimnitz and Kempema, 1984). Note: the term "shear" is misleading as many of the grounded features within this zone are created through a mix of compression and shear and include local pileups (linked to shoals), rough areas of jumbled ice rubble, and linear ridges (see Figure 15). WMO (1970) forms a primary reference to internationally accepted sea ice nomenclature.
- Pack Ice
    - » Transition region of active deformation in moving ice adjacent to the fast-ice edge (part of the shear zone bridging between the fast ice and pack ice).
    - » Seasonal pack comprised of mainly first-year ice that clears through the summer to a point of maximum retreat from shore in the last half of September (ice edge positions in the third week in September are used by NOAA to monitor the effects of Arctic climate change).
    - » Polar pack zone of predominantly (over 5/10 concentration) multi-year ice ranging from two to more than 10 years in age. Normally located far off the coast, the polar pack edge can advance into the proposed drilling areas in extreme years. This has not happened during the drilling season over the past decade.

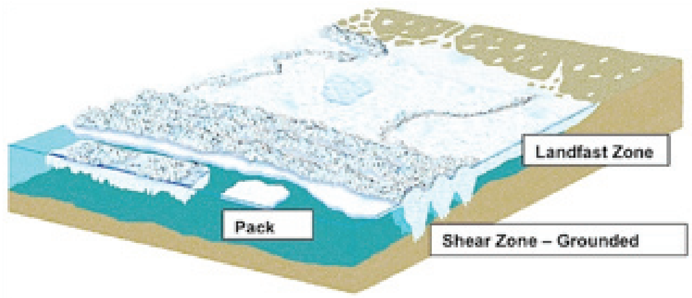


Figure 4: Beaufort Sea Ice Zones (after Mahoney et al., 2005)

Figure 5 shows schematically how the composition of the ice cover changes with water depth and time in the central Alaskan Beaufort Sea in an average year. The diagram begins with the start of the ice season in October and end with September, coinciding with the maximum expanse of open water.

Differences in ice composition and the timing of break-up and freeze-up are summarized below, using the broad geographic subdivisions shown in Figure 5. Note that the water depths used to describe the different areas are intended as a general guide (actual depths can vary greatly from year to year):

- Inshore: refers to the area between the coast and approximately the 10-foot water depth, demarking the approximate boundary of sea ice overflood in late May/early June and including the zone of bottom fast ice (typically out to 6 feet of water). The lagoon areas inshore of the Barrier Islands are included here. This is the first area to clear in the spring (often by mid June) and the first to freeze at the beginning of October.
- Nearshore: refers to the area of floating fast ice between about 10-foot and 80-foot water depths, beginning with the first stable sheet in shallow water by late October and expanding into deeper water as the winter progresses (reaching close to 100 feet water in late winter from April to May). Water depths and coastal geometry play major roles in controlling the stability and morphology (surface roughness) of this fast ice zone. This is the second area to clear in early to mid July.

- Offshore: refers to the area of often mobile pack ice in water deeper than 70 feet in early winter and 100 feet in later winter. From December to June this area is characterized by predominantly first-year ice of varying thickness in vast floes with 95 percent ice coverage interspersed with distinct coast-following leads. This is the last area to clear in early August and the last to freeze-up in mid to late October.

The following sections trace the changing composition of the ice cover in different water depths, starting with the onset of melt and initial clearing along shore in early June, moving through the periods of extensive open water in August and September and the first appearance of a new ice cover in October, and ending with the development of thicker, more consolidated pack ice in winter (Atwater, 1991; Vaudrey, 2000; Dickins and Oasis, 2006).

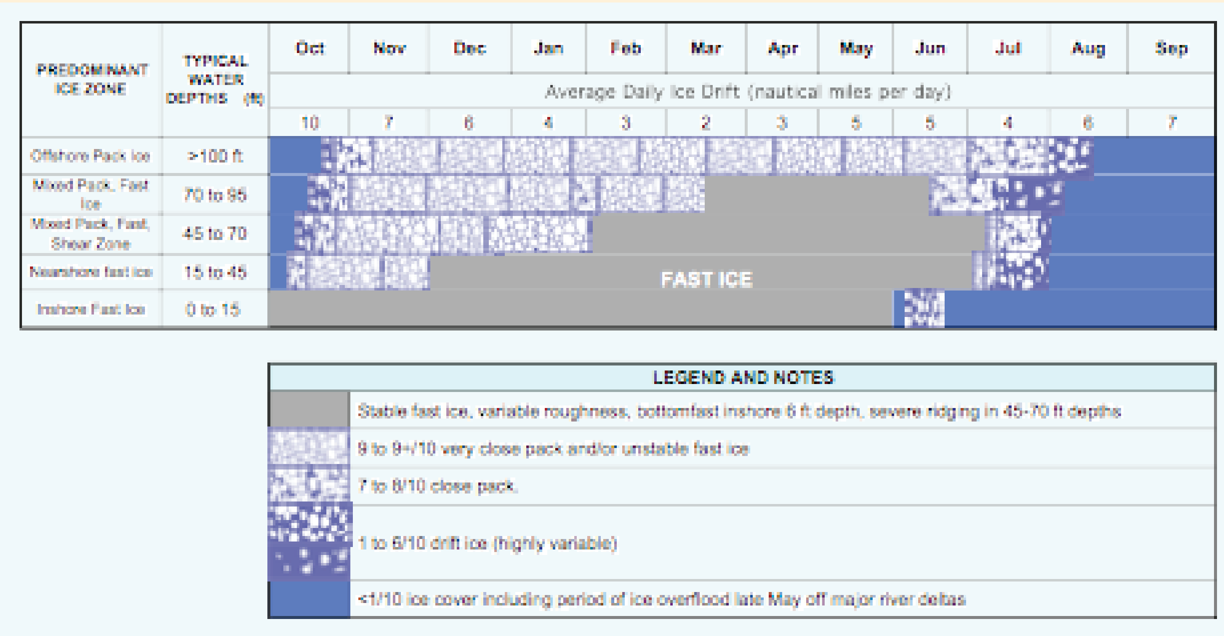


Figure 5: Graphic showing the typical central Alaskan Beaufort Sea ice environment in different water depths, beginning with freeze-up in October.

The following sections trace the changing composition of the ice cover in different water depths, starting with the onset of melt and initial clearing along shore in early June, moving through the periods of extensive open water in August and September and the first appearance of a new ice cover in October, and ending with the development of thicker, more consolidated pack ice in winter (Atwater, 1991; Vaudrey, 2000; Dickins and Oasis, 2006).

Break-up

This period is characterized by a high degree of annual variability with a period of three to six weeks where dynamically changing ice concentrations mark the transition from winter to summer. Following the river ice overflood in late May, initial open water corridors appear along the shore and in the lagoon areas by mid June in most years. Beyond the Barrier islands, fast ice remains stable and intact off Prudhoe Bay (vicinity of Northstar) until July 4 on average. By that time the sheet ice has ablated through melt to a variable thickness of 2 to 4 feet with numerous open holes and extensive melt ponds (see Figures 6 and 7 below).

Following initial fracturing and movement of the fast ice, the ice sheet nearshore deteriorates into increasingly thinner and smaller floes (shown below in Figure 8), leading to open water in late July in the vicinity of 30- to 50-foot water depths.

Ice concentrations in deeper water sites (100 feet and beyond) in the last half of July are highly variable, ranging from open water in unusually mild years (e.g. 1998) to a more typical condition of 7-8/10 thick first-year ice with floe sizes in the medium to big category (300-1,500 feet to 1,500-6,500 feet).

Figure 6: Fast ice in the final stages of melt off Stump Island, near West Dock June 24, 1996. Inshore lagoons (left of photo) are ice-free.

Photo: D. Dickins

Figure 7: Fast ice immediately prior to break-up around Seal Island (now Northstar), July 8 1983. Remains of the winter ice road to shore are clearly visible.

Photo: K. Vaudrey

Figure 8: **ACS oil spill response vessel navigating through rotting ice floes nearshore in July.**
Photo: Alaska Clean Seas

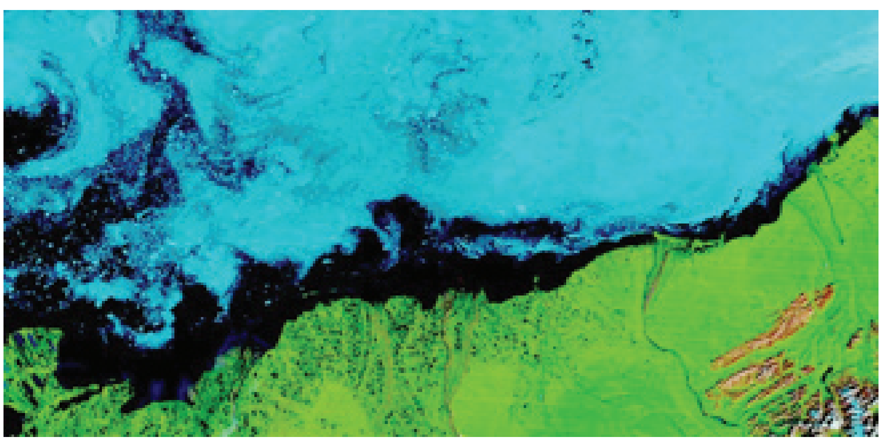


Figure 9: **MODIS image showing ice conditions on July 29, 2002 (NASA). Harrison Bay (left) to Barter Island/Kaktovik (right).**

Intermediate ice concentrations (4-6/10) are less common and generally occur for a brief period of one to two weeks in late July and early August. Based on an ice database created for Sivulliq (1997-2006) ice concentrations reduce to an average value of 3/10 by August 7. The satellite image in Figure 9 shows conditions on July 29, 2002 between Cape Halkett (Harrison Bay) and Barter Island.

Summer

Ice conditions in the summer months are largely dictated by the wind patterns; persistent easterly winds tend to move the pack away from shore, promoting extensive clearing along the coast, while westerly winds tend to keep the pack ice close to shore and limit the extent of summer clearing (e.g. 2006). Open water (defined as ice less than 1/10) predominates at Shell's central Beaufort drilling locations from August 20 to October 10, reaching a maximum extent in the latter half of September. Ice incursions (often referred to as "invasions") can occur after the initial clearing when the offshore pack ice is driven into shore by sustained westerlies, and/or when thick grounded remnants of the shear (Stamukhi) zone float free in August and drift through the offshore area. Summer ice incursions occurred in three of the past 10 years and lasted from one to three weeks. The summer of 2006 was unusually severe, with pack ice remaining in the drilling areas until September 18, followed by less than three weeks of open water (Canadian Ice Service web archives).

Freeze up

The transition from the first appearance of new ice to almost complete ice cover (8/10 or more) occurs rapidly with a small range of variability from year to year (±8 days). The first ice (grease and new) appears along the coast and in the lagoon areas near Prudhoe Bay in the first week of October on average. This ice generally becomes stable within one week following initial freeze-up (see Figure 10). In deeper water (typically 10 to 50 feet) north of the Barrier Islands, the first continuous sheet of new ice forms on average by October 15 (Dickins and Oasis, 2006). Initial ice-growth rates are extremely rapid with the sheet ice reaching 12 inches (marking the transition from young ice to thin first-year) nearshore within two weeks after the first occurrence of grease ice at the coast (Vaudrey, 2000). By late October, ice movements inshore of the 30-foot water depth are infrequent, and the young ice is considered relatively stable out to the vicinity of the Northstar production island off Prudhoe Bay (Vaudrey, 2000).

Shell's drilling locations in deeper water tend to be the last to form new ice, in the period from October 15 to 22 on average. In the initial stages, freeze-up is characterized by substantial amounts of grease ice/slush in the water before the first consolidated new ice sheet appears (see Figures 11 and 12). Offshore, the ice takes longer to consolidate and progresses in a patchy non-linear fashion as wind and waves act to break up the grey ice as it forms (less than 6 inches). Rafting is common as the thin ice fractures and rides over itself, forming multiple layers shown in Figure 12. A range of different ice forms will commonly occur at the same time in a localized area. In the last half of October the ice sheet offshore is still thin enough to be easily broken in the wake of a moving vessel (see Figure 13).

Figure 10: Freeze-up with nilas and grey ice in October off the Barrier Islands near Prudhoe Bay

Photo: K. Vaudrey

Figure 11: **Icebreaker proceeding through grease ice in late October.**

Photo: D. Dickins

Figure 12: **Drillships operating in the Canadian Beaufort in late October in the 1970's.**

Photo: Dome Petroleum

Figure 13: **Young ice less than 12 inches thick breaking in the wake of an icebreaker in October. Thick multi-year floe in background.**

Photo: D. Dickins

Winter

The early winter (November/December) period is characterized by an expanding fast-ice zone, increasing in stability as the ice sheet thickens and becomes more able to resist early winter storms. During this period, the fast ice edge expands seaward from an average water depth of 15 feet in October and November to 40 to 45 feet in December off Flaxman Island (similar longitude to Sivulliq), for example (Eicken et al., 2006). It is important to understand how the different ice regimes develop through the winter in the event that a well release continued after freeze-up, possibly leaving a portion of the spill trapped within moving ice.

In the early winter period, the pack ice in the vicinity of the 100-foot water depth is comprised almost totally of first-year ice. Ice charts in the October to December time frame over the past 10 years (1997-2006) reported no multi-year ice beyond trace amounts (much less than 10 percent coverage). The offshore pack ice at this time consists of a broad mix of ice ages, from young ice less than 12 inches thick to thin first-year ice up to 30 inches. Once the ice begins to raft and rubble in November, level ice becomes the exception and over 30 percent of the ice surface offshore deforms into ridges or rubble.

Landfast ice growth curves for Prudhoe Bay show the average inshore ice thickness at the end of November as 25 inches (see Figure 14). The average level ice thickness offshore always will be significantly less than nearby fast ice, reflecting the simultaneous occurrence of different stages of ice development in the same general area (see Figure 13).

During the winter period from January to April, the fast ice continues to expand seaward, reaching average depths beyond 70 feet of water by February. The maximum fast ice extent occurs in the period from March to May. In those months, recent studies at the University of Alaska Fairbanks show that the average water depths at the fast-ice edge reach 100 feet, much deeper than the 60-foot boundary often discussed as the average boundary in earlier reports.

East/west oriented leads (shore following) are common within the winter pack-ice zone in water depths from 100 to 150 feet (see Figure 15). Many of these leads have widths ranging from hundreds of meters to miles, and continue uninterrupted for long distances. Eicken et al. (2006) provides an extensive analysis of lead distributions, orientations and dimensions.

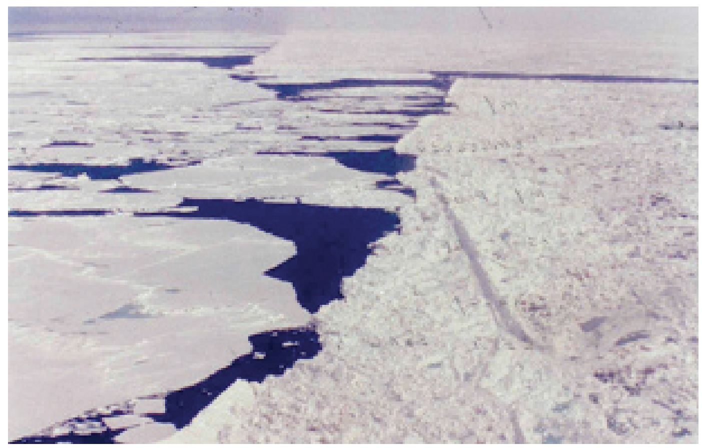


Figure 15: Fast-ice edge off the Alaska North Coast with flaw leads and thin first-year floes offshore. Note sharply defined line of shear ridging.

Photo: K. Vaudrey.

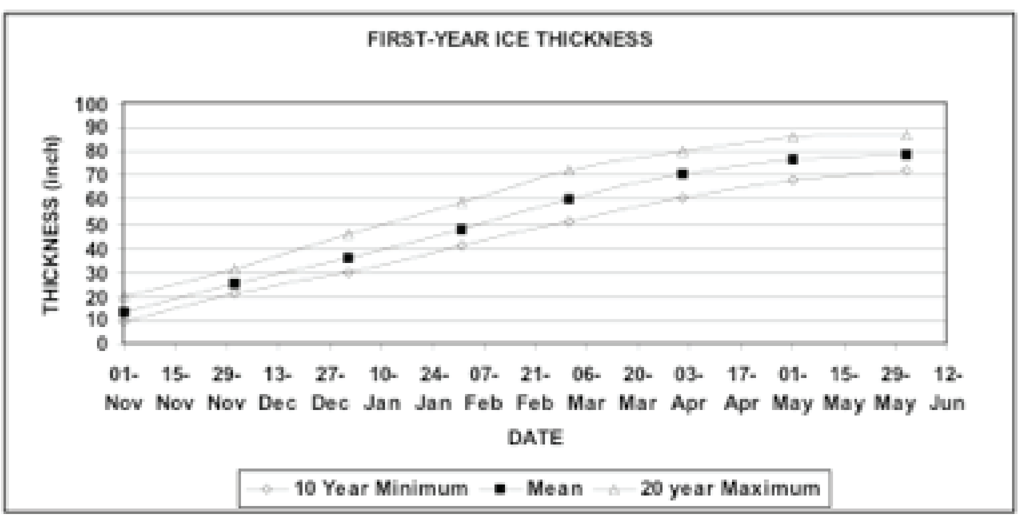


Figure 14: Landfast ice growth curves (Vaudrey, 2000)

Pack ice in the winter moves in an episodic, meandering fashion with a net westerly drift in response to wind and currents. Ice speeds are at their maximum (typically 5 to 7 nm per day) with large expanses of young ice offshore in November and December, and gradually decrease as the ice pack thickens and becomes more consolidated through January and February. Average speeds reach their minimum in March and April with typical values in the 1.5 to 2.7 nm per day range (Melling and Riedel, 2004). The general ice movement direction is predominantly to the northwest; however for 40 to 60 percent of the time historical satellite drift buoys show the ice moving without any persistent sense of direction.

Table 1 shows the percent of observations where daily average movements exceeded a given value during break-up and freeze-up. Data was extracted by Vaudrey (2000) from a number of different studies using satellite buoys covering the nearshore and continental shelf area of the Alaskan Beaufort during the years 1975-87 and three specific buoys deployed between Northstar and West Dock during the 1996 break-up season (Vaudrey and Dickins, 1996). It should be noted that short-term ice drift speeds (periods of 2 to 6 hours) could be significantly higher, in the range of 1 to 2 knots using 4 to 5 percent of the wind speed as a rule of thumb.

As the winter progresses and the ice becomes more consolidated, there often are periods of weeks or more with little or no ice movement in deep water. For example, a long-term ice drift record over seven seasons shows that the monthly incidence of no ice motion typically increases from around 20 percent in November to between 30 and 40 percent of the total time in December (Melling and Reidel, 2004). During these static periods, the boundary between the fast ice and pack ice zones becomes blurred and indistinct as the two zones merge.

When the pack ice is in a more typical dynamic drift mode, the fast-ice boundary is clearly defined by a zone of shear and compression ridges (see Figures 4 and 15). Many of these ice features are grounded in water depths out to 80 feet, and can reach surface elevations up to 50 feet in some cases. The most active shear zone of severe ice deformation tends to be fairly narrow and concentrated between about 50 and 70 feet of water, with no distinct east/west trends in severity.

Weather and Sea State

The marine climate is summarized briefly here to highlight a number of key parameters affecting spill response:

- Winds;
- Low Visibility;
- Hours of Daylight;
- Waves and Currents.

Winds

In general, winds in the area are considered gentle to moderate and generally from the east-northeast (predominant at 40-60 percent of the time) or west-southwest (20 to 40 percent of the time). Northerly or southerly winds occur for less than 7 percent of the time. Storm winds tend to be westerly. In terms of wind speed, a moderate breeze of 15 knots or more can be expected in the range of 24 percent of the time in August to 37 percent in October. Gale force winds in the range 34 to 40 knots (Beaufort Force 8) are extremely rare, occurring for less than 2 percent of the time in the windiest months (September to February) and less than 1 percent of the time for the rest of the year. Figure 16 shows the historical monthly wind speed exceedence for the Prudhoe Bay area.

The wind field over the Beaufort Sea continental shelf is not well captured by winds derived from existing forecasting and climate centers using coastal stations. The strong influence imparted by the Brooks Range in winter and the sea breeze effect (imparted by the land-ocean-ice thermal gradients) in summer can lead to marked differences between the wind regime at the coast and offshore. These effects need to be taken into account in modeling oil spill drift (MBC Applied Sciences 2003).

Table 1

Exceedence Probability Distribution of Ice-Drift Speeds

	PERCENT > NET DAILY ICE MOVEMENT RATE (knots)							AVERAGE
SEASON	>0.2	>0.4	>0.6	>0.8	>1.0	>1.5	>2.0	SPEED (knots)
Freeze-Up	50.0	17.7	8..1	3.8	1.9	0.4	0.3	0.3
Break-Up	34..0	14.4	6.2	2.8	0.8	0	0	0.2

Visibility

In the event of adverse weather, flight limitations caused by adverse ceiling and visibility combinations may restrict offshore operations and response. For example, Shell's company policy on Visual Flight Rules (VFR) sets the lower limits at 500 feet cloud ceiling or 1 mile forward visibility. Low visibility conditions occur most frequently during the break-up period in July and August (approximately 25 percent cumulative, probability less than one mile). In contrast, the freeze-up period in October is characterized by a lower probability of low visibility (17 percent less than one mile).

Daylight

Hours of daylight are close to their greatest extent during break-up in August (21 hours average for the month) and reduce through the summer to average 11 hours in October. In practice, twilight significantly increases the available operational time beyond the strict definition of daylight (sunrise to sunset).

Waves and Currents

Ocean circulation combines the effects of nearshore currents, shelf currents, and subsurface currents. Nearshore circulation is heavily influence by the complexities along the Beaufort coastline. Continental shelf currents in the Beaufort Sea are primarily wind driven. Mean water flow under the ice is westward but weak (less than 0.1 feet per second), primarily tidal and polarized in the along-shore direction. During the period of open water and or loose ice from early July to mid-October, surface currents are highly variable and significantly correlated with the alongshore winds. Speeds typically exceed 0.3 feet per second and maximum currents can reach 3 feet per second (close to 2 knots). Reference Okkonen and Weingartner (2003).

The coastline in proximity to the exploration area is generally a low wave-energy environment. Tides in the Beaufort Sea are mixed semidiurnal with a very small range, about six to 12 inches. Waves are primarily from the east and northeast and are predominantly generated during the open water season. For much of the summer period (July to August) the close proximity of sea ice will effectively prevent sea states from developing to the extent predicted from the standard relationship of Beaufort wind scale and sea state (http://www.srh.noaa.gov/). The appearance of new ice in October effectively limits the achievable wave heights within a few weeks after initial freeze-up off the coast.

Potential maximum sea states during the period of maximum open water (mid-August to mid-October) can be estimated from the standard Beaufort scale relationship. For example a moderate breeze of 11-16 knots (Force 4) will typically result in a wave height of 3.5 to five feet. This condition represents a realistic upper bound for effective at-sea containment and recovery and from the wind statistics shown above would be exceeded approximately 30 percent of the time in September, corresponding to the time when the maximum extent of open water occurs off the Alaskan Beaufort Sea coast.

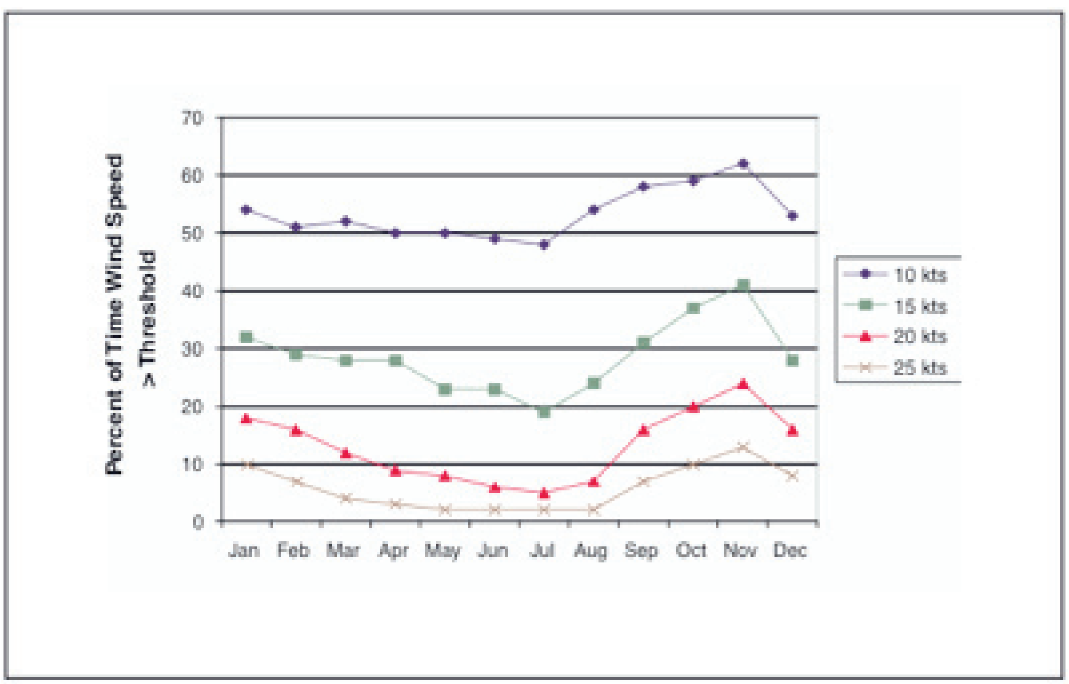


Figure 16: Monthly wind speed exceedence. Source: Vaudrey (2000) based on long-term data for the Prudhoe Bay area

OPERATIONAL PREPAREDNESS

Planning

Shell's c-Plan, the AES Response Tactics Manual and the ACS Technical Manual cover specific oil spill recovery operations involving conventional containment and recovery systems applicable to open water (i.e., approximately 1/10 concentration or less) and a range of ice conditions. Many of these tactics illustrate ways to intercept oil with an open-apex U-boom configuration so that thin or scattered oil slicks can be concentrated for mechanical recovery or captured downstream of the open-apex for burning within a fire boom.

Open-water clean-up techniques utilizing a variety of boom configurations and skimming systems are proven through offshore industry operations worldwide. Such response systems are capable of high-oil encounter rates with effective daily recovery capacities exceeding Shell's Worst Case Discharge (WCD) of 5,500 bbl/day. Conventional open-water countermeasures can be used with a high degree of success in the moderate wave climate of the Beaufort Sea during most of the open-water period in a typical year (generally from mid-August to mid-October). When ice is present, the planning process must incorporate the need for different countermeasures options focusing on the potential for oil removal by burning. This section describes the overall scope of preparedness, planning and spill response organization developed by Shell to recover and/or eliminate oil during periods when ice is present, using a mix of burning and mechanical recovery strategies.

Preparedness through planning encompasses:

- A thorough understanding of oil and ice interactions.
- Acquisition of rugged, state-of-the-art response equipment to work in ice.
- Provision of ice-strengthened vessels/barges to enable the effective execution of mechanical and in situ burning response options.
- Training of response personnel to work safely and effectively under harsh conditions.
- An appreciation of the need to work with the environment, using the beneficial effects of low temperature and ice wherever possible to enhance spill control (see following).

Cold Climate Challenges and Opportunities

Two of the most important factors influencing Arctic oil spill response planning are the distribution and amount (area coverage) of sea ice in the Beaufort Sea. As described previously in the Introduction and Operating Environment, the timing of when ice is present is strongly related to water depth. Coastal areas generally experience ice-free conditions for four to five weeks longer than locations in deeper water. There is considerable variability from year to year. For example, the Sivulliq location experienced more than 13 weeks of open water in 1998 and less than four weeks in 2001 and 2006 (Canadian Ice Service web archives).

Coping with the dynamic nature and unpredictability of ice can pose a significant challenge for spill response. Experience has shown, however, that low temperatures and ice also can enhance spill response and reduce environmental impacts under certain conditions. For example:

- Low air and water temperatures generally lead to greater oil equilibrium thicknesses that result in reduced spreading rates and smaller contaminated areas. These beneficial effects greatly reduce the potential for direct oil impact with natural resources while providing an opportunity for much higher oil encounter/removal rates using mechanical recovery and burning operations.
- Evaporation rates are reduced in cold temperatures and ice. As a result, the lighter and more volatile components remain for a longer time, thereby enhancing the ease with which the oil can be ignited.
- The wind and sea conditions in the Beaufort Sea are considerably less severe than most open-ocean environments. The regional presence of ice dampens wave action and often limits the fetch over which winds might otherwise create larger fully developed waves.
- While any ice, even in concentrations as low as 1-2/10, can preclude the effective use of oil containment boom, responders still may operate with short-boom extensions and skimmers to maneuver among ice pieces and intercept oil in open areas.
- When ice concentrations preclude the use of any boom, the ice serves as a natural barrier to

the spread of oil and help concentrate the oil for recovery with stationary skimmers dipped into discrete pockets of oil. The natural containment of oil against ice edges leads to thicker oil films that enhance the effectiveness of burning.

- With high ice concentrations (9/10 or more), most of the spilled oil (especially from a subsea blowout) will rapidly become immobilized and encapsulated within the ice. This oil is then effectively isolated from any direct contact with biological resources (marine or bird life).
- Oil encapsulated within the ice is isolated from any weathering processes (evaporation, dispersion, emulsification). The fresh condition of the oil when exposed (e.g., through ice management or natural melt processes) enhances the chances for effective combustion.

In addition to factors related to the operating environment, the characteristics of the spill source affecting the nature and distribution of the initial oil release will strongly influence the potential for oil recovery and choice of optimum response strategy.

The spill scenarios associated with Shell's exploration operations in the Beaufort Sea involve the release of oil and gas from a subsea blowout (above-water releases are more commonly associated with fixed production drilling structures). In a subsea blowout, oil will be released to a relatively small area on the water, with initial slick widths of typically less than 500 feet. Even with the gas-induced flow of oil and water toward the surface and the resulting radial spread of oil outward from the source, the initial spill area will be localized and relatively easy to contain and/or deflect with booms in open water (Allen, 1991).

Because of the likely release of large quantities of natural gas and vapors from the surfacing oil, early ignition of the gas is likely as soon as the drilling rig moves off location. This deliberate action is not only prudent for safety reasons (eliminating the possibility of accidental, ignition when vessels are close by), but also to potentially eliminate significant quantities of oil through combustion.

Personnel and Equipment

Shell and its contractor, ASRC Energy Services (AES) Response Operations LLC, together with Alaska Clean Seas (ACS), maintain a comprehensive inventory of equipment to initiate and sustain mechanical recovery and in situ burning operations throughout the proposed drilling season. Originally formed as ABSORB in 1979, ACS has a long history of supporting its member partners as a full-response organization with over $50 million in specialized equipment inventory designed to cope with accidental releases at any time of the year. AES is a leading oil and gas service company owned by the largest Alaskan Native Regional Corporation, with headquarters in Anchorage and operations in Alaska, Canada, Louisiana and Russia. Resources and expertise cover spill response management and contingency planning. AES' roots in North Slope field operations date back to the earliest development of the Prudhoe Bay oilfield in the 1960s.

In order to cover the full range of anticipated conditions, Shell's c-Plan incorporates a comprehensive training program that includes all aspects of mechanical containment and recovery and in situ burning with and without fire booms.

Shell's offshore and nearshore oil spill response plans emphasize the use of mechanical cleanup as the preferred mode of response. Under many conditions however, in situ burning may provide the safest and most effective means of spilled oil. Reflecting the importance of this response option, ACS conducts in situ burn training under a variety of conditions at nearly all of its North Slope locations. Courses include classroom instruction and field exercises involving basic combustion theory, guidelines for safe operating procedures, and gelled fuel mixing and Heli-Torch deployment. Shell/AES personnel also are instructed on these same guidelines and procedures as they relate to the potential use of controlled burning offshore. Shell and AES continue to work closely with ACS in order to maintain a team of trained in situ burn responders.

Table 2 provides an inventory summary of key pieces of spill response equipment assigned to be on location during the drilling season for mechanical containment and recovery and burning.

Table 2

Offshore Oil Spill Response Equipment

Vessels/Barges	
Oil Spill Response Vessel (OSRV)	(1) 300' Response Vessel Nanuq with 12,000-bbl storage (see Figure 18)
Oil Spill Response Barge (OSRB)	(1) 200' Barge Endeavor & Tug with 16,800-bbl storage
Arctic Tanker	(1) 513,000-bbl Tanker for recovered oil and water
Skimming Boat	(1) 47' Self-Propelled Boat with built-in skimmers
Workboats	(6) 34' Workboats for boom towing
Mini-Barges	(4) 249-bbl barges for recovered oil and water
Skimmers	
Large Brush Skimmers	(4) Lamor 1,290 bbl/hour (over-the-side 5-brush system)
Vertical Rope Mop Skimmers	(2) 504 bbl/hour (over-the-side skimming system)
Built-in Brush Skimmers	(2) Lamor 517 bbl/hour (skimming units in 47' boat)
Mini-Brush Skimmers	(2) Vikoma 88 bbl/hour (over-the-side skimming units)
Boom	
Offshore Boom	(8) 656' (each) Deflection/Containment Boom Systems
Fire Boom	(2) 500' (each) Water-Cooled Fire Boom Systems
Misc.	
	(3) 100-bbl towable bladders Flares for remote ignition; Pumps, power packs and reels for boom, skimmers and lightering operations, sorbents, tools, etc.

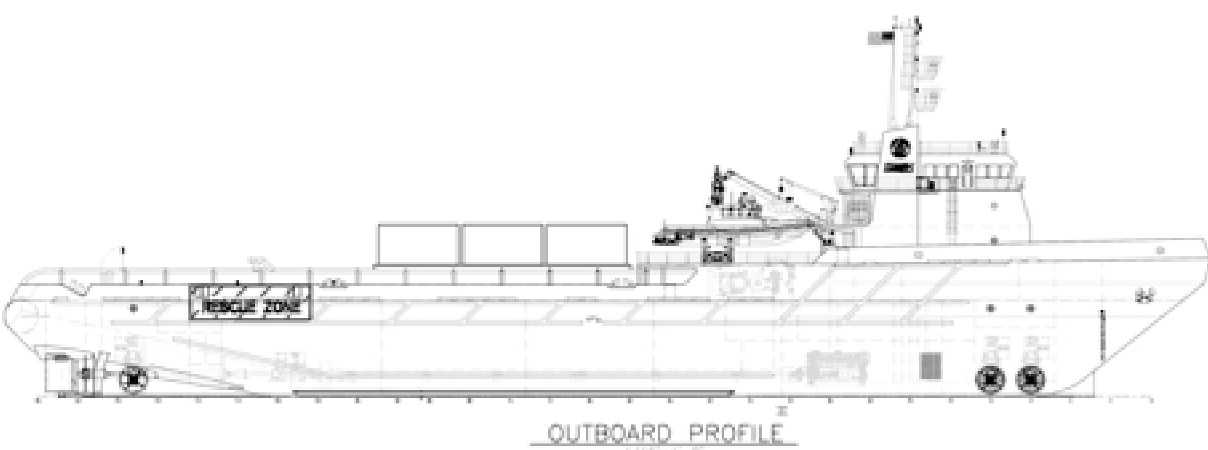


Figure 17: Shell's dedicated ice strengthened Oil Spill Response Vessel Nanuq (as configured at the design stage – additional equipment such as pedestal cranes added during construction).

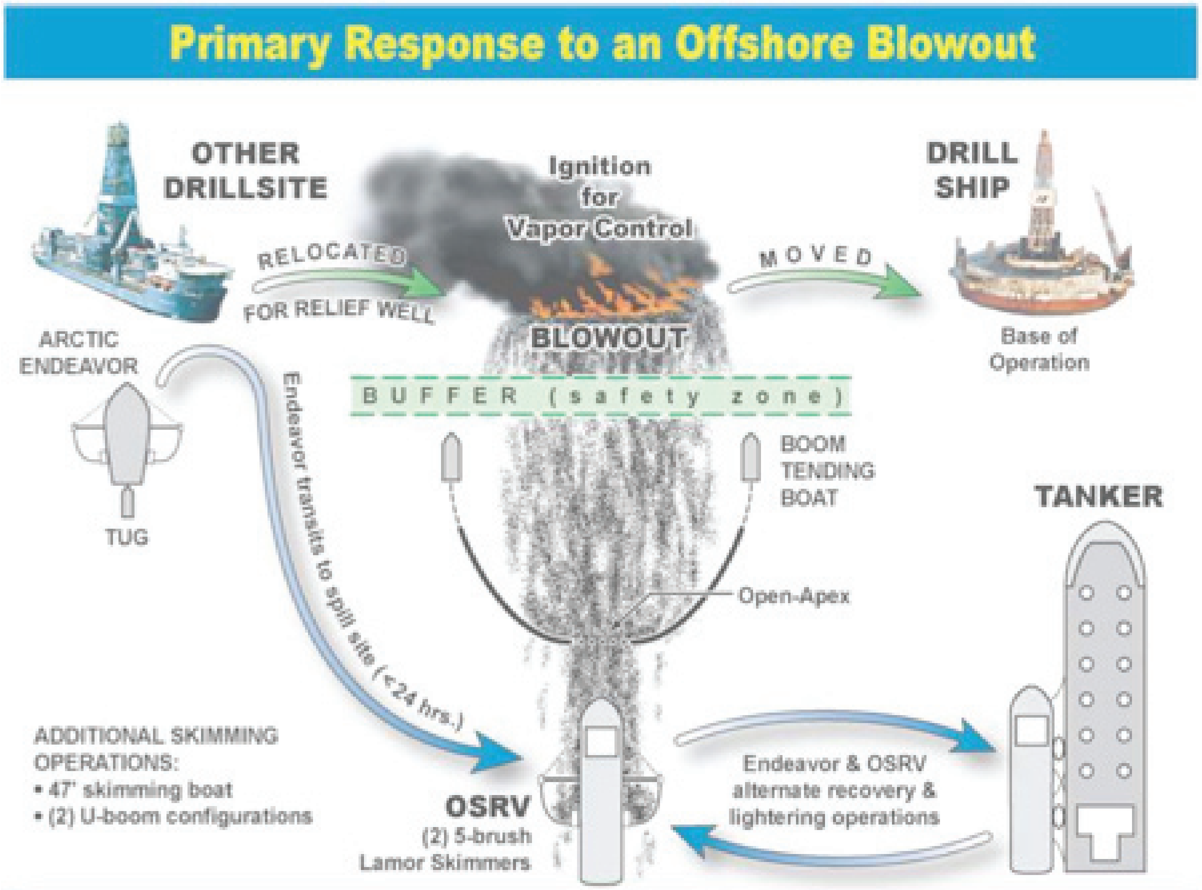


Figure 18: Schematic representation showing a possible deployment of key vessels and response systems to deal with an offshore blowout.

The above illustration (Figure 18) shows an example of how the support vessels, rigs and key response systems could be deployed in the event of a blowout (actual layout would depend on a range of environmental and safety factors).

In addition to the program-specific inventory detailed in Table 2, ACS will provide their established personnel and vessels, barges, skimmers, etc. to support nearshore and shoreline protection, containment and recovery operations from bases at West Dock and Deadhorse. Most of the equipment necessary to support this effort could be deployed and ready for use from the main base near Deadhorse within hours of a call-out. In addition, Shell and ACS will stage critical response equipment at key locations such as Pt. Thomson and Kaktovik to protect Priority Protections Sites designated by the North Slope Sensitive Areas Work Group (SAWG).

Table 3

Additional In Situ Burning Equipment (ACS-owned)

Equipment	Quantity
Conventional Fire Boom (to supplement Shell's offshore water-cooled fire boom)	19,000 feet (20", 30" & 40" skirts)
Heli-Torches	(6) 55-gallon aerial ignition systems
Heli-Torches	(2) 300-gallon aerial ignition systems
Sure-Fire Gel Mix	1,200 lb. (for creation of gelled fuel)
Air Deployable Igniters	> 1,400 (for aerial & surface ignition of oil)
Gelled Fuel Batch Mixers	(2) large systems to mix gelled fuel

The ACS inventory of specialized response equipment to support a large-scale burn operation is summarized in Table 3.

In addition to the specific equipment listed here, Shell, ACS and AES maintain full logistical support capabilities for controlled burning, including: Boom tending vessels, helicopters and vessels to transport and deploy fire boom and ignition systems. These resources and equipment are concentrated at Deadhorse Airport, West Dock and the main ACS warehouse at Prudhoe Bay.

Shell works closely with government agencies and other stakeholders to ensure that plans are in place for the potential use of in situ burning. The ACS Technical Manual (Tactics Description B-1) contains steps that will be followed in reaching the decision to use in situ burning. As part of the approval process the "Alaska Regional Response Team Application for In Situ Burning" will be submitted to the Unified Command according to the ARRT Unified Plan for Alaska, App. 2, Annex F, In Situ Burning Guidelines for Alaska (ADEC et al. 2007 Rev.). An incident-specific burn plan is contained within the application.

SPILL RESPONSE COUNTERMEASURES

The purpose of this section is to present the state of knowledge regarding the capabilities and limitations of different recovery and removal strategies under a range of environmental conditions including open water and ice. The principal techniques of mechanical containment and recovery and in situ burning are addressed while focusing on ice factors and fundamental principles that most influence effectiveness. In addition, brief descriptions are provided on recent developments in oil spill detection and tracking, and on research involving dispersants as a potential oil spill response option for cold climates.

Mechanical Containment & Recovery

The rapid physical containment and recovery of oil at or near the source of any spill is always a primary goal. Depending upon the nature of the spill and environmental conditions at the time of release (e.g., oil discharge rate, ignited vs. unignited, surface vs. subsurface release, wind and sea conditions, ice concentration, current, visibility, etc.), it may not be practical or safe to conduct an immediate containment and recovery operation. The timing and location of all spill response measures (relief well drilling, medical evacuation, containment and recovery, spill surveillance, etc.) would be determined by the operating conditions and safe distances from the blowout. As discussed earlier, an early decision to ignite the gas released at source would likely be made in consultation with the Unified Command to protect personnel and vessels from any accidental ignition. Safety of personnel is always the highest priority in a response operation. Any decision to place people with boats, booms, skimmers, and other equipment at or near the source will depend upon qualified professionals making frequent assessments of changing conditions.

When safety considerations and ice conditions permit mechanical recovery tactics will include the use of broad-swath, open-apex deflection booms to intercept oil and funnel it to skimming vessels equipped with large, ice capable five-brush skimmers (see Figures 19 and 20). This equipment was developed in Finland for cold-climate recovery operations specifically involving viscous oil emulsions. As listed in Table 2, the four skimmers located on the two primary Oil Spill Response Vessels (even derated to 20 percent of nameplate capacity) have Expected Daily Recovery Capacities (EDRCs) that are more than four times the potential daily Worst Case Discharge (WCD) of 5,500 barrels of oil per day (approximately 229 bbl/hour). The Alaska Department of Environmental Conservation (ADEC) WCD planning standard involves 5,500 bopd from a blowout with a continuous release for 15 days. Shell has prepared its response capabilities, however, based on the Mineral Management Service (MMS) requirement of 5,500 bopd for 30 days.

A smaller self-propelled skimming boat (47 feet long with built-in brush skimmers and separate over-the-side skimmers) complements the larger recovery systems to enable teams to rapidly adapt to a dynamic mix of open water and ice conditions possible at any time during the drilling season. Depending upon the nature and amount of oil being released, these different systems can be used in a number of configurations to intercept a wind/current-driven swath of oil from the source, or to maneuver independently to access the heaviest concentrations in a widespread slick.

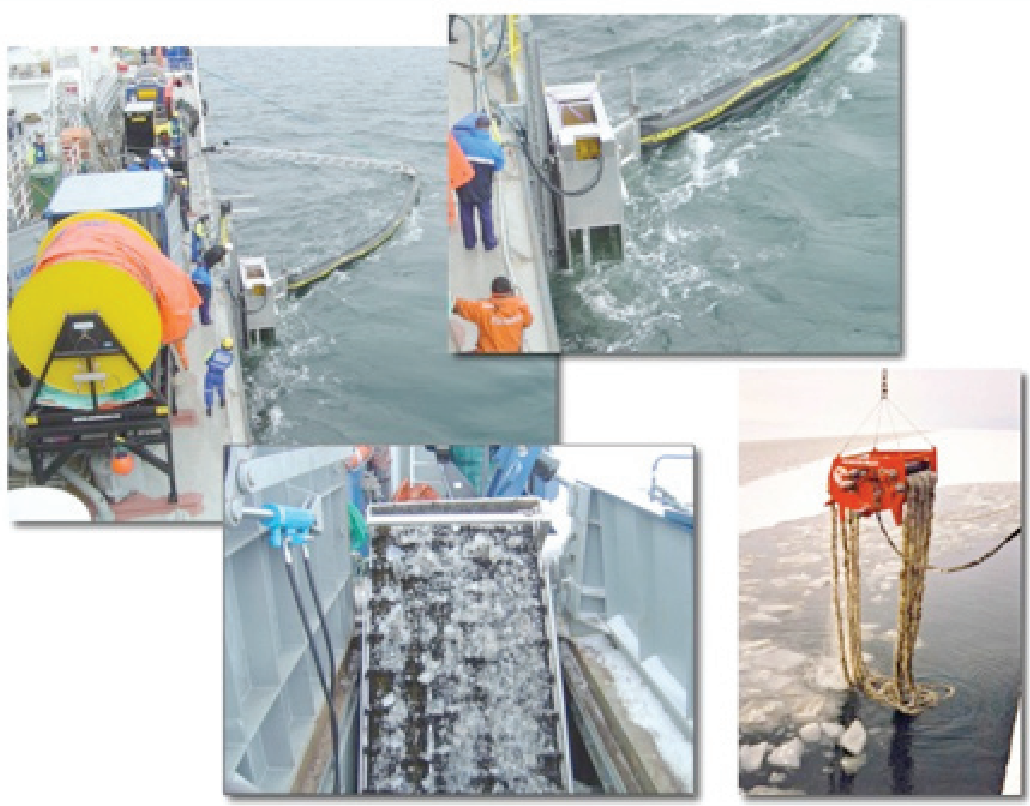


Figure 19: Examples showing offshore mechanical recovery systems in open water, and brush and rope, mop skimmers with ice.

Photos: Lamor and ACS

High-volume, viscous-oil pumps are available on both the Nanuq (OSRV), shown in Figure 17, and the Endeavor (OSRB) so that the onboard temporary oil/water storage tanks (12,000 bbl and 16,800 bbl, respectively) can be offloaded quickly to a 513,000-bbl, double-hulled storage tanker, anchored in close proximity to the drill sites.

At some point, as ice concentrations increase beyond very open drift conditions (1-3/10) almost all advancing-mode skimming systems will experience numerous interruptions and loss of effectiveness. Large, open-apex mechanical recovery systems can encounter unacceptable levels of ice build up in ice concentrations as low as 1/10 (exacerbated when there are high levels of grease, slush or brash in the area). The upper ice concentration limit for any given system of booms and skimmers will depend on a number of factors. For example, ice charts may show 3-4/10 ice, while in reality, the ice may be concentrated in patches or strips separated by large areas of open water. Under these conditions, it may be possible to effectively maneuver booms and recover oil without being interrupted by ice (see Figure 20).

Crews can move toward smaller, more maneuverable vessels with side arms and potentially continue to recover oil at reduced encounter rates in ice for some time after operations with the larger systems have ceased. At some point, continued operations with any containment boom become impractical. Mechanical recovery can then only continue at low rates with over-the-side skimmers (e.g. brush and rope mop) to access pockets of oil trapped between ice cakes and floes or in leads (see Rope-mop example in Figure 19 above).

Figure 20: ACS response vessel maneuvering a mini-barge through highly variable concentrations of drift ice, illustrating conditions where limited containment and recovery, or burning of oil could take place in the openings between floes.

Shell has evaluated ways to extend the window of opportunity for continued use of high-volume recovery systems relying on booms and skimmers through concepts such as ice deflection and ice management.

Ice Deflection: The key feature of this concept involves deflecting light-to-moderate ice concentrations upstream of the blowout to create a protected area in the lee of the deflection system. The resulting cleared area could provide a relatively ice-free zone for the continued use of booms for a period after the initial freeze-up. Studies, including large tank tests, have shown that substantial vessels or barges (approximately 300 to 400 feet in length) could be held sideways in currents of 1 to 2 knots with broken ice up to 1 foot to 1 ½ feet thick in ice concentrations of at least 5/10 to 6/10 ice cover, thereby deflecting the broken ice around one or both ends of the barge/vessel (see Figure 27 following).

Ice Management: There are other tactics involving the management of ice with icebreakers, and the movement of oil through broken ice with prop-wash from vessels (see Figure 29) or the use of fire monitors to flush oil toward a potential collection site. The application of ice management concepts also may be used to enhance in situ burning strategies as discussed later.

Even with these enhancements for containment and recovery, the rate at which individual skimmers can access oil quickly diminishes as ice concentrations increase. At some point, the continued use of open-water containment and recovery systems becomes impractical. Fortunately, there is a transition or crossover where, as ice concentrations increase, the containment lost through ice interference with conventional open-water booms is replaced by the natural containment provided by the close proximity of individual ice floes.

Even relatively thin ice with a low freeboard (i.e., the portion of the ice above the water surface) can provide an effective barrier to oil spreading. Although it is possible under these conditions to access isolated pockets of oil with skimmers directly (i.e., working without booms), the rapid removal of large volumes of oil will require a different approach involving burning.

As the effectiveness of mechanical recovery declines in expanding ice coverage, Shell would work closely with the Unified Command to continually assess the potential for controlled burning. A lack of significant oil recovery, potentially accompanied by a deteriorating safety environment for crews and vessels, may trigger a decision to refocus the response effort, relying on the ignition and combustion of oil contained naturally by the ice.

Figure 21: **Open water burning of crude oil at sea after ignition with a Heli-Torch during the Newfoundland Offshore Burn Experiment (1993).**

Photo: Environment Canada

Controlled In Situ Burning

This section focuses on the application of in situ burning under a range of open-water and ice situations, with and without fire booms. In situ burning with ice containment provides a unique way to eliminate oil quickly, efficiently and safely at times when continued use of booms is not possible. With the opportunity of aerial ignition, personnel and equipment are no longer exposed to the increased risks of on-deck marine operations during freeze-up conditions. In open-water and light-ice (or managed-ice) conditions, burning with fire booms provides a valuable alternative strategy to mechanical recovery.

This section summarizes the scientific principles and physical processes involved with in situ burning of oil on water (see Fig. 21) and in the presence of ice (see Figure 27). The goal is to better understand the capabilities, strengths and weaknesses of controlled burning in a range of environmental conditions. Specialized strategies designed to enhance burning with natural-ice containment are developed further in a following section.

Basic Combustion

For an oil slick on water or ice to become ignited, the oil must be thick enough to insulate itself from the water beneath it. The igniter can heat the surface of thickened oil to the flash point temperature at which the oil produces sufficient vapors to ignite. To sustain ignition, however, the oil must be thick enough to allow the surface of the oil to remain at or above its fire point (typically a few degrees higher than its flash point). The rules-of-thumb for minimum ignition thickness are listed in Table 4.

Table 4

Minimum Ignitable Oil Thickness on Water

Adapted from Buist et al. (2003)

Oil Type	Minimum Thickness
Light Crude and Gasoline	~ 0.04 inches
Weathered Crude and Middle-Distillate Fuel Oils (Diesel and Kerosene)	~ 0.08 to 0.12 inches
Residual Fuel Oils and Emulsified Crude Oils	~ 0.4 inches

The oil removal rate for in situ oil fires is a function of fire size (or diameter), slick thickness, oil type and ambient environmental conditions. For most large (greater than 10 feet diameter) fires of unemulsified crude oil on water, the "rule- of-thumb" is that the burning consumption rate is ~ 0.14 inches per minute (in/min). Lighter fuels burn faster and heavier oils and emulsions burn slower as shown in Table 5.

Burn rate also is a function of the size of the fire. Crude oil burn rates increase from approximately 0.04 in/min with three-foot diameter fires to approximately 0.14 in/min for 15-foot fires and greater. In situ burns on melt pools may consume oil at such rates depending upon the size of the pool and the thickness and condition of the oil. For very large fires, on the order of 50 feet in diameter and larger, burn rates may decrease slightly because there is insufficient air in the middle of the fire to support the higher rate of combustion. As fire size grows to the 50-foot range, oil type has a lesser effect on burn rate for the same reason.

Relatively small areas can yield high elimination rates. For example, a 100 foot pool could burn at 10 barrels of oil per hour (boph) or more, and an 8,000 foot pool (only 100 feet in diameter) could burn on the order of 1,000 boph or more.

Burn Effectiveness

With an estimate of the initial thickness of a fully contained slick, or a measure of the burn time, it is relatively easy to estimate oil removal efficiency by burning. Oil removal efficiency by in situ burning is a function of the following key factors:

- Initial thickness of the slick;
- Thickness of the residue remaining; and
- Amount of the slick's surface that burned.

The consensus of research on spill response with in situ burning of oil on open water and with solid and broken ice is that burning is a highly effective technique, with removal rates of 85 percent to 95 percent or more in most situations (e.g. Shell et al. 1983, S.L. Ross 1983, Norcor 1975, Dickins and Buist 1981, SL Ross and DF Dickins 1987, Allen 1990, Allen 1991, Allen and Ferek 1993).

In a recent experimental spill under solid ice in Norway, 900 gallons of crude oil were allowed to surface naturally through the ice and then burned with an overall removal efficiency of 96 percent. A portion of this oil was exposed to weathering on the ice surface for more than one month before being successfully ignited (Dickins et al., 2006).

A considerable amount of research also has demonstrated the potential for in situ burning in broken ice, with and without slush. This research includes several small-scale field and

Table 5

Burn Removal Rates for Large Fires on Water

Adapted from Buist et al. (2003)

Oil Type/Condition	Approximate Burn/Removal Rate
Gasoline > 0.4 inches thick	0.18 inches per minute*
Distillate Fuels (diesel and kerosene) > 0.4 inches thick	0.16 inches per minute
Crude Oil > 0.4 inches thick	0.14 inches per minute
Heavy Residual Fuels > 0.4 inches thick	0.08 inches per minute
Slick 0.2 inches thick[1]	90 percent of rate stated above
Slick 0.08 inches thick[1]	50 percent of rate stated above
Emulsified oil (percent of water content)[2]	Slower than above rates by a factor equal to the water content percent

**Estimates of burn/removal rate based on experimental burns (accurate to within ±20 percent).*

Notes to Table 5:

1 Thin slicks will naturally extinguish, so this reduction in burn rate only applies at the end of a burn.

2 If ignited, emulsions will burn at a slower rate almost proportional to their water content (a 25 percent water-in-crude-oil emulsion burns about 25 percent slower than the unemulsified crude).

tank tests (SL Ross et al. 2003, Shell et al. 1983, Brown and Goodman 1986, Buist and Dickins 1987, Smith and Diaz 1987, Bech et al. 1993, Guénette and Wighus 1996) and one significant field test (Buist and Dickins, 1987). Many of the tank tests involved oil placed in a static test field of broken ice, resulting in substantial slick thicknesses for ignition. Tests in unrestricted ice fields or in moving ice have indicated that the film thickness (and related efficacy of in situ burning) may be sensitive to ice concentration and relative movements of the floes (Singsaas et al. 1994). The success of a burn in ice is clearly dependent upon the tendency for the ice floes to naturally contain the oil, thereby maintaining a suitable thickness of the oil for combustion.

The presence of emulsifications and/or brash ice and slush significantly affects the ability to ignite the slick and the achievable burn effectiveness. The state of knowledge in these two areas is summarized as follows.

> *Burning of Emulsified Oil:* Compared with unemulsified slicks, emulsions are much more difficult to ignite and, once ignited, display reduced flame spreading and more sensitivity to wind and wave action. Stable emulsion water contents are typically in the 60 percent to 80 percent range with some up to 90 percent. The oil in the emulsion cannot reach a temperature higher than 100 degrees Celsius (°C) until the water is either boiled off or removed. The heat from the igniter or from the adjacent burning oil is used mostly to boil the water rather than heat the oil.
>
> The following points summarize the effect of water content on the removal efficiency of weathered crude emulsions:
>
> - Little effect on oil removal efficiency (i.e., residue thickness) for water contents up to about 12.5 percent by volume;
> - A noticeable decrease in burn efficiency with water contents above 12.5 percent, the decrease being more pronounced with weathered oils;
> - Very little, if any, success in burning emulsions with water contents of 25 percent or more; and
> - Some crudes form meso-stable emulsions that can burn efficiently at water contents of 25 percent or higher. Paraffinic crudes appear to fall into this category.

The feasibility and efficiency of burning oil from a subsea blowout in the Beaufort Sea will depend in large part upon the nature of the oil as it surfaces and upon the composition and amount of ice present. Studies within Shell have revealed that oil and gas from a subsea blowout (best represented by gas and oil flow rate characteristics from nearby reservoirs) could result in the atomization of oil due to turbulence from the gas plume. With this type of release, small droplets of oil would rise, along with the expanding gas, toward the surface where induced currents could then carry the oil droplets out radially from the source.

Little, if any, emulsification is expected during the transport of oil toward the surface; however, within hours (depending upon the actual oil, wind/sea conditions, etc.) emulsification could reach levels that would make ignition difficult to impossible. These are factors that must be considered in planning to use in situ burning at or immediately downstream of the blowout.

Fortunately, emulsion formation is slowed dramatically by high ice concentrations and may not be a significant operational factor in planning in situ burns on solid ice or naturally contained in higher concentrations of broken ice.

Burning in Broken Ice and Slush: Based on extensive testing in the ACS wave tank at Prudhoe Bay, S.L. Ross et al. (2003) provides guidelines for burning thin slicks in broken ice with brash and slush, particularly relevant during the break-up and freeze-up shoulder seasons. General rules for minimum ignitable thickness and oil removal rates for burning thin slicks of crude oils on brash and/or slush with broken ice are as follows:

- The minimum ignitable thickness for fresh crude on frazil ice or small brash ice pieces is up to double that on open water, or about 0.04 to 0.08 inches.
- The minimum ignitable thickness for evaporated crude oil on frazil ice or small brash ice pieces can be higher than on open water, but is still within the range quoted for weathered crude on water, about 0.12 inches with gelled gasoline igniters.
- For a given spill diameter, the burn rate in

calm conditions is about halved on relatively smooth frazil/slush ice and halved again on rougher, brash ice. Wave action slightly reduces the burn rate on open water, but the halving rule seems to apply in waves as well.

- The residue remaining on broken ice in calm conditions is about 50 percent greater than that on open water, or 0.06 inches. The residue remaining on brash or frazil ice in waves is slightly greater than in calm conditions, at about 0.08 inches.

Under the right conditions, in situ burning of oil can be efficient and rapid in broken ice conditions as long as the following basic criteria are met (S.L. Ross et al. 2003):

- The spilled oil should be contained and thicker than its minimum ignitable thickness (a thickness of 0.08 to 0.12 inches could result in a 50 to 70 percent removal efficiency; a 0.4 inches thickness, typical for oil that has been collected in a boom or wind-herded against ice or a shoreline could yield a 90 percent removal efficiency).
- For a given spill diameter, the burn rate in calm conditions is about halved on relatively smooth frazil/slush ice and halved again on rougher, brash ice.
- The oil to be ignited should not exceed an emulsification of approximately 25 percent water-in-oil.
- As with open-water burns, ignition is easiest when winds are below approximately 20 mph.

Burn Extinguishing Thickness and Residue

An in situ oil fire extinguishes naturally when the slick burns down to a thickness that allows enough heat to pass through the slick to the water to cool the surface of the oil below the temperature required to sustain combustion. Currents (primarily wind driven) maintain the oil thickness in the apex of a fire-resistant boom under tow, or against a stationary ice edge. Over time, the fire slowly decreases in area until it reaches a size that can no longer support combustion. This wind (or current) herding effect can increase overall burn efficiency, but it extends the time required to complete each burn.

The thickness at which an oil fire on water extinguishes is related to the type of oil and initial slick thickness as presented in Table 6. For most slicks, the extinguishing thickness corresponds to the minimum thickness for ignition summarized in Table 4. Slicks over 2 inches at ignition may experience a greater extinguishing thickness. Secondary factors include environmental effects such as wind herding of slicks against barriers, and oil weathering. Note that winds in excess of 20 knots often make the ignition of oil extremely difficult.

The residue from an efficient (greater than 85 percent removal) in situ burn of crude oil 0.4 to 0.8 inches thick is a semi-solid, tar-like layer that has an appearance similar to the skin on an old, poorly-sealed can of latex paint that has gelled. For thicker slicks, typical of what might be expected in a towed fire boom (about 6 to 12 inches), the residue can be a solid. Burn residue is usually denser than the original pre-burn oil, and does not normally spread due to its increased viscosity or solid nature.

Tests indicate that the burn residues from efficient burns of heavier crude oils less than 32 °API may sink once the residue cools, but their acute aquatic toxicity is very low or nonexistent. The "In Situ Burning Guidelines for Alaska" (ADEC, U.S. Environmental Protection Agency (EPA) and U.S. Coast Guard (USCG), March 2001) state:

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

Table 6

Fire Extinguishing Slick Thickness

Adapted from Buist et al. (2003)

Oil Type/Initial Slick Thickness	Extinguishing Thickness
Crude Oil up to 0.8 inches thick	0.04 inches
Crude Oil up to 2 inches thick	0.08 to 0.12 inches
Distillate Fuels any thickness	0.04 inches

required to have a plan for residue collection."

Prince William Sound RCAC (2004) further considered the potential risks to marine life posed by burn residues:

> "ANS burn residues were composed almost exclusively of high boiling point fractions (HBPF). From an environmental perspective, the burning removes most if not all of the lower-molecular weight aromatic hydrocarbons, which tend to be the more toxic and more bio-available components of the crude oil (Fingas and Punt, 2000). Bioassays with water from laboratory- and field-generated [Newfoundland Offshore Burn Experiment (NOBE)] burn residues of Alberta Sweet Mix Blend showed little or no acute toxicity to sand dollars (sperm cell fertilization, larvae, and cytogenetics), oyster larvae, and inland silversides (Daykin et al., 1994). Bioassays using NOBE burn residues showed no acute aquatic toxicity to fish (rainbow trout and three-spine stickleback) and sea urchin fertilization (Blenkinsopp et al. 1987)."

Burn Safety

Any decision to burn is made in close consultation with the regulatory agencies through the Unified Command. Safety procedures and planning in accordance with established guidelines are emphasized throughout the training, preparation and conduct of in situ burning operations. A trial burn may be required to confirm the anticipated plume drift direction and dispersion distances downwind before authorization is granted. Response teams would implement any special provisions (e.g. public notices and warnings required by the Unified Command, natural resource agencies and public safety agencies) to protect nearby human populations and environmentally sensitive areas.

In situ burns will be limited to sites that are a minimum distance, generally three or more miles upwind of human populations. Safe distances under different conditions are outlined in the "In Situ Burning Guidelines for Alaska." (ADEC, EPA and USCG, 2001; Rev. April 2007) and in Bronson (1998). In situ burning will not be authorized unless the operation meets established EPA public health regulatory standards in terms of airborne particulates. Burn operations may be stopped if the plume contacts or threatens to contact the ground in any populated area during the operation.

Table 7

Safe Working Distances From a Fire

Personnel Exposure Time	Minimum Distance from Fire (fire diameters)
Indefinite	4
30 minutes	3
5 minutes	2

In situ burns are continually monitored to ensure that fire does not spread to any uncontained oil nearby and that burns are conducted at safe operating distances from all vessels and personnel on location. The safe working distances from an in situ fire on water depend on the size of the fire and the exposure time as summarized in Table 7.

Dispersants as a Possible Future Arctic Response Option

There is growing evidence from scientific testing that dispersants could play a significant role in future Arctic spill contingency plans (Owens and Belore, 2004; Brown and Goodman, 1996). The application of chemical dispersants is recognized worldwide as an environmentally acceptable and highly efficient means of rapidly eliminating spilled oil offshore under the right conditions. Dispersants provide an invaluable third response option when strong wind and sea conditions make mechanical cleanup and in situ burn techniques unsafe and/or ineffective. Under these conditions the treatment of spilled oil with chemical dispersants, is actually enhanced by the mixing energy provided by breaking waves that hinder other response operations. This advantage, combined with the potential to treat large areas quickly with aerial application systems, makes dispersants an essential tool for most offshore oil spill response organizations (See Figure 22).

Countering the potential benefits of timely dispersant application, is the need to have adequate water depth (typically 10 meters, or approximately 30 feet) for the dispersed oil to mix within the water column, degrade and be diluted sufficiently to minimize the possibility of any harmful exposure to marine resources.

Numerous laboratory and field studies have demonstrated that a decision to use dispersants can, under the right conditions, provide a clear net environmental benefit compared to the impacts of not using the dispersant. The trade-off involves accepting short-term, localized impacts to the near-surface water column in order to significantly reduce the potential long term impact to the overall marine environment from a spill that remains at the water surface, spreads over large areas, and reaches shore. Dispersants do have the potential to impact the environment if used with improper dosage control, and/or at a time when sensitive marine life (mostly planktonic) are present within the surface waters beneath the treated slick. Great progress continues to be made, throughout the United States and abroad to educate the public, government agencies and response organizations about the advantages and disadvantages of chemical dispersants. Ecological Risk Assessment (ERA) workshops, conducted in many regions, help to pave the way for an accurate understanding of dispersants. Many of the misconceptions regarding dispersant use, such as the belief that they are ineffective in cold climates, are now being addressed and better understood through improved laboratory, tank and full-scale trials. Recent industry and government sponsored tests under realistic conditions in near-freezing water and with ice are showing promising results with existing and new formulations of dispersant, even with weathered, viscous oils.

While there is growing evidence that dispersants could play a significant role following a blowout in Arctic waters, Shell has not proposed their use at this time for offshore operations in the Beaufort Sea. Substantial stockpiles of chemical dispersant (Corexit 9527 and 9500) are available in Alaska, along with aerial application systems that could be operated from helicopters and fixed-wing aircrafts. Should there be a need to use this option, Shell could call upon the resources of ACS, AES, Alyeska Pipeline Service Company, and others to implement a dispersant application program using Deadhorse, Alaska as a staging location. Such an operation would only be initiated after review by federal, state and local representatives of the Regional Response Team (RRT), and approval by the Unified Command (UC).

Detection and Tracking of Oil

The tracking of spilled oil during the open-water period is relatively easy because of the extended periods of daylight in the Arctic and the fact that a blowout would be a fixed, known source of release from the seabed. Response personnel will be available immediately to travel by boat to identify, map and report the leading edge of any spilled oil. Within hours, helicopter surveillance teams can join in the tracking of oil from the air.

Figure 22: Aerial dispersant application systems.

Photos: A. Allen

Tracking can be aided with Forward Looking Infrared Radar (FLIR) systems, Global Positioning Systems (GPS), digital cameras, etc. In addition, tracking buoys and various types of radar reflectors can be launched from vessels on location at the beginning of a spill and at appropriate intervals thereafter to help track the oil. Existing technology is available to support the ongoing detection and tracking of oil on water and spread among open drift ice up to 6/10.

Conditions of high ice concentrations, slush and brash in the water at freeze-up, and situations where the oil is trapped beneath floes present major challenges. Tracking oiled ice is possible by using similar proven technologies applicable for open water (satellite buoys, radio transmitters etc.). Specialized ice-strengthened beacons have been used successfully for many years to track ice movements over an entire winter season throughout the polar basin. Detection and mapping (spill boundaries) is more difficult.

Techniques for detecting and tracking oil under ice include Tactics T-3 (Oil Under Ice Detection) and T-4A (Discharge Tracking in Ice) detailed in the ACS Tactics Manual. In addition to these procedures, recent research funded by MMS and industry (including Shell) proves the ability to detect and map oil trapped under sea ice using surface operated, portable ground penetrating radar (GPR) (Dickins, et al., 2006 and 2005). Ongoing research is evaluating the feasibility of using airborne radar with sufficient power and resolution to detect and map oil trapped under ice from a low-flying helicopter.

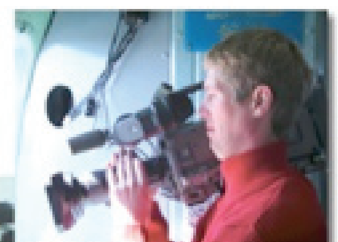
Off-the-shelf Ground Penetrating Radar (GPR) systems are capable of airborne (helicopter) mapping oil on the ice surface buried under snow. ACS recently (2006) acquired a GPR system to deal with the potential for pipeline spills under snow in the Prudhoe Bay fields.

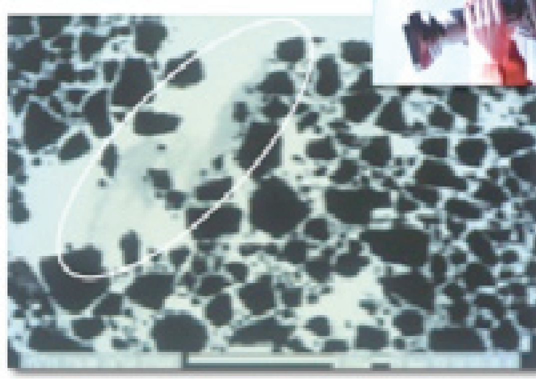
A comprehensive, ongoing (2007-2009) Joint Industry Program (JIP) managed through SINTEF Norway and sponsored in part by Shell, is aimed at developing improved Arctic spill response techniques. This initiative includes a dedicated project managed by DF Dickins Associates, concerned with testing and evaluating the capabilities of different remote sensing systems to detect and map oil in a variety of ice conditions: laser fluorosensor, GPR, UV/IR, SLAR, Radar Satellites, enhanced marine radar etc. Figure 23 shows a variety of detection, tracking and mapping technologies.

Ground penetrating radar Tests in Norway 2006 (Dickins/Boise State/SINTEF

Twin Otter survey aircraft (Bald Mountain Scientific)

Ice Tracking Buoy (Metocean)





Infrared aerial photography of an experimental spill in pack-ice (SINTEF)

Figure 23: **Examples of oil spill detection, tracking and monitoring technologies including satellite tracking buoys, surface and airborne ground penetrating radar, and infrared airborne video (FLIR).**

STRATEGIES FOR BURNING IN ICE

The previous section reviewed the full range of spill response countermeasure options with a focus on the capabilities of different technologies and strategies in a Beaufort Sea environment. This section addresses many of the key issues involved with burning oil released from a subsea blowout under a broad range of environmental conditions in water depths, currents and ice conditions representative of Shell's offshore operations in the Beaufort Sea. The discussion begins by exploring the possibility of removing oil directly through deliberate ignition at source and then moves on to considering strategies for achieving successful burn operations in different ice and current situations including: Drifting thick floes early in the season, summer ice incursions, new ice formation at freeze-up, and high concentrations of rapidly growing ice in early winter.

Oil Removal by Ignition at Source

Once the drilling rig has been moved off location, and all vessels are at a safe distance, the Federal On-Scene Coordinator (FOSC) may elect to have the gas plume ignited for safety reasons. Once state and federal approval is granted to conduct controlled burns, efforts could get under way to deploy equipment at or downstream of the blowout. Before discussing strategies for controlled burning, it is important to understand the limitations and possibilities for removing a portion of the spill through ignition at source.

The primary reason for igniting the gas cloud at source is one of safety, to prevent any subsequent accidental ignition from vessels or equipment. In most cases, the gas will burn without consuming a significant percentage of the oil slick. However, under very calm conditions, it is possible to remove a large portion of the oil discharge volume by igniting the gas. The two main spill response scenarios associated with ignition at source are summarized as follows.

1. **Typical wind and currents:** The initial distribution of the surfacing oil droplets in open water could involve a surface area with a diameter in the order of 500 feet with the largest drops comprising most of the release volume rising quickly near the center. Depending on the residual and surface wind driven currents at the time, the oil droplets could surface into a relatively clear water surface, where their initial spreading would result in slicks that are too thin to support combustion (likely on the order of four one thousandths of an inch (0.004 inches). Under these conditions, combustion could effectively consume the free gas surfacing at the blowout; however, the relatively thin slicks would not support sustained combustion of the oil (typically requiring a 0.04 to 0.08 inch oil thickness).

2. **Calm or Light Winds:** In the case of little or no surface current, there would be an increased accumulation of oil droplets at the surface allowing for the build up and re-coalescence of those droplets into a layer that could readily support combustion. Calm conditions (say zero to five knot winds) occur between 15 percent and 18 percent of the time from August to November. Under these conditions, the heat generated by the burning of free gas will likely ignite vapors associated with the increased concentration of oil over the blowout. The increase in the naturally sustained burn area could remove a substantial portion of the surfacing oil. In addition, the heated air rising above the blowout would produce a thermally-induced wind along the surface working radially in toward the fire. Even a relatively light breeze of this kind could further reduce spreading of the oil and maintain the necessary oil thickness for improved, sustained combustion. In this situation, it would not be necessary to use fire boom or to position personnel and equipment anywhere near the surfacing oil. With the right combination of conditions, effective burning of a significant portion of the blowout could take place simply because of the natural accumulation of oil at and near the spill source.

Controlled Burning in Different Ice Conditions

In most cases, direct intervention through deliberate controlled burning will be required to remove a significant percentage of the spilled oil. In situ burning provides the only effective, safe solution to the problem of maintaining high volume removal rates in ice concentrations that might preclude the effective use of large mechanical recovery systems. The constant supply of fresh oil combined with the natural containment and limited wave action provided by the ice creates a favorable set of conditions for burning to eliminate large volumes of oil from a blowout.

There have been a number of incidents in the U.S., Canada and Scandinavia where burning with ice has been approved and carried out operationally as a key part of the response effort (see Table 8).

The means by which controlled burning can take place over a range of conditions from open water and light ice to almost complete ice cover at freeze-up are explored in the following sections organized around three general categories of ice conditions:

- Open Water (up to 1/10) and light ice cover (2-4/10);
- Intermediate Concentrations sufficient to contain oil (6-8/10); and
- High Ice Concentrations & New Ice in Early Winter (9-9+/10).

Strategies for Controlled Burning in Open Water and Light Ice Cover (2-4/10)

Two primary modes of operation exist for controlled burns in open water and minimal ice cover (1-3/10) involving fire boom.

1. "Collect, Relocated and Burn" oil is collected with fire boom in a towed U-boom configuration, followed by the ignition of the contained oil after the boom is relocated away from the main slick.
2. "Station-keeping" approach, with the fire boom held in a stationary condition at or very close to the spill source. During this approach, the oil is burned in place as it is collected, avoiding any need to relocate the operation prior to ignition.

The selection of the most effective mode will depend upon the environmental conditions at the time of the spill, including wind and wave conditions, currents and ice concentration. Each mode is described below according to the steps involved in implementing and sustaining the operation. Ice deflection concepts are introduced as a means to extend the use of fire booms into higher ice concentrations.

Collect, Relocate and Burn Mode (See Figure 24)
When wind and wave conditions allow for the effective use of booms (typically with short-period wind-waves of three-to-five feet or less), fire boom can be towed at approximately three-fourths knot through oil slicks until reaching their holding capacity. They can then be relocated a safe distance away from the source, combustible uncontained oil slicks, and vessels so that the contained oil can then be ignited safely. Fire booms also may be

Table 8

Selected Experiments and Events Involving Operational Oil Burning in Ice

Year	Country	Description	Events	Lessons
1969	Finland	*Raphael*	Oil burned in high ice concentrations	Very high removal rates achievable with burning in ice – 85 percent of visible oil. Lampela (2000)
1970	Sweden	*Othello/Katelysia*	Oil burned among ice and within pools	Oil contained by ice can be burned
1970	Canada	Deception Bay	Tank farm rupture spilling diesel on and under fast ice nearshore	400,000 gallons of diesel fuel in tidal cracks and on the ice surface - burned (Ramseier 1973)
1977	USA	Buzzards Bay barge spill	Fuel oil spilled from a barge in moving broken ice	Incendiary devices dropped from helicopters to ignite oil pools in winds of 19 knots. Typical burns lasted 10 to 20 minutes with flames jumping from pool to pool
1979	Canada	*Imperial St. Clair*	Fuel spill in ice	Oil spill in ice readily burned in river environment
1983	Canada	*Edgar Jordain*	Grounded vessel with fuel onboard in Arctic	Fuel burned off the vessel and surrounding ice

used in this mode by intercepting oil at a safe distance downstream of its source, possibly with the aid of open-apex, oil-concentration booms, and once again relocating the boom with its oil to a safe location for ignition.

Aerial ignition with gelled fuel from a Heli-Torch or with other ignition devices is carefully coordinated with all other activities on the water and in the air (see example shown in Figure 21 – preceding Section). ACS and AES personnel, as well as pilots who fly the Heli-Torch, practice the techniques involving the controlled burning of oil at sea, taking into account prevailing weather conditions, oil pool size and distribution, and the need for strict adherence to established safety practices.

Ignition of the contained oil may involve hand-held igniters released from one of the boom-towing boats, or it could be accomplished with a Heli-Torch flown at right angles (to the direction of tow) approximately 25 to 50 feet above the leading ends of the fire boom U-configuration. In either case, the ignition source(s) drift back into the contained oil, providing ample time for the helicopter with its torch or for responders on the boom towing boats to prepare for the actual ignition of the oil.

While oil is burning within the first U-configuration, a second fire boom could be collecting oil, possibly back at the open-apex deflection boom. When the first burn is completed and the burn residue is recovered, that boom could then be towed back to relieve the ongoing oil collection operation. Fire booms, typically 500 feet in length, can hold between 500 and 1,000 bbl of oil.

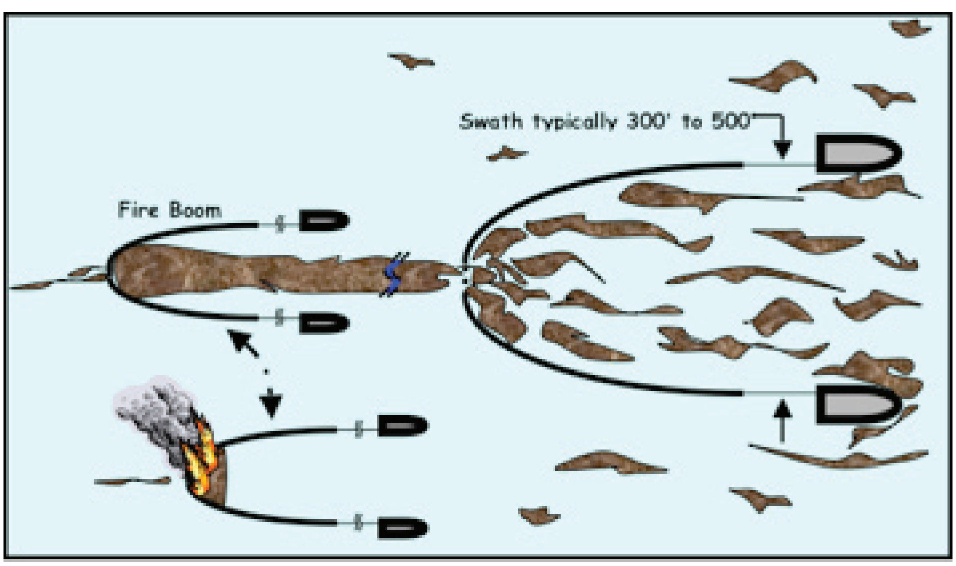


Figure 24: Collection, relocation and burning of spilled oil downstream of open-apex boom configuration.

With oil collection times of a few hours, there would be ample time for the relocation and burn of oil in a separate fire boom system. Two fire booms could alternate the collection and burning of oil at a rate that could keep pace with the WCD of 5,500 bopd (approximately 229 bbl/hour).

Station-Keeping Mode (See Figure 25)

In the "station-keeping" mode it may be possible to capture a major percentage of the oil as it surfaces and burn it before it spreads downstream. Two boom-tending boats would be positioned at a safe distance upstream of the blowout, using long towlines and cooling water feed lines (needed for the water-cooled Hydro-Fire boom). The U-boom configuration could remain on location, burning oil continuously and in close proximity to the burning of free natural gas released along with the oil. This potentially simpler mode of operation is possible as long as the relative surface currents past the boom (over the ground) are less than 1 knot to avoid excessive oil entrainment but more than zero to allow the oil to move naturally away from the blowout and into the boom. This limited ability to cope with any significant surface currents or calm condition leads to more emphasis being placed on the Collect/Relocate/Burn mode (see Figure 24 above).

Strategies for Burning in Intermediate Ice Concentrations (6-8/10)

This category encompasses situations at break-up in early August and during summer ice incursions when ice concentrations are too high to allow the use of conventional booms or fire booms, but sufficient to naturally contain the oil from spreading and encourage the development of thick films amenable to burning.

Broken ice moving over the blowout in concentrations greater than 5/10 could help facilitate the response in a number of ways. The floes would tend to dampen wind waves and swell, reduce radial surface spreading over the blowout, and promote re-coalescence of the surfacing oil droplets in the reduced water surface area between ice floes. Under these conditions, there would be an increased potential for the accumulation of oil thicknesses that could support sustained combustion.

As long as the ice concentrations do not become excessive (e.g over 8/10) and/or the ice comes under pressure, there will be sufficient oil contained between floes to support combustion in localized burns. As in the previous open-water scenarios, if surface currents over the blowout drop close to zero, the increased accumulation of oil between oil floes would only enhance the overall efficiency of burn. Induced radial currents over and adjacent to the blowout may prevent much of the oil from adhering to the underside of ice cakes and small floes. In that case, the proportion of the discharge available for burning could be much larger than the limited proportion of open water would suggest.

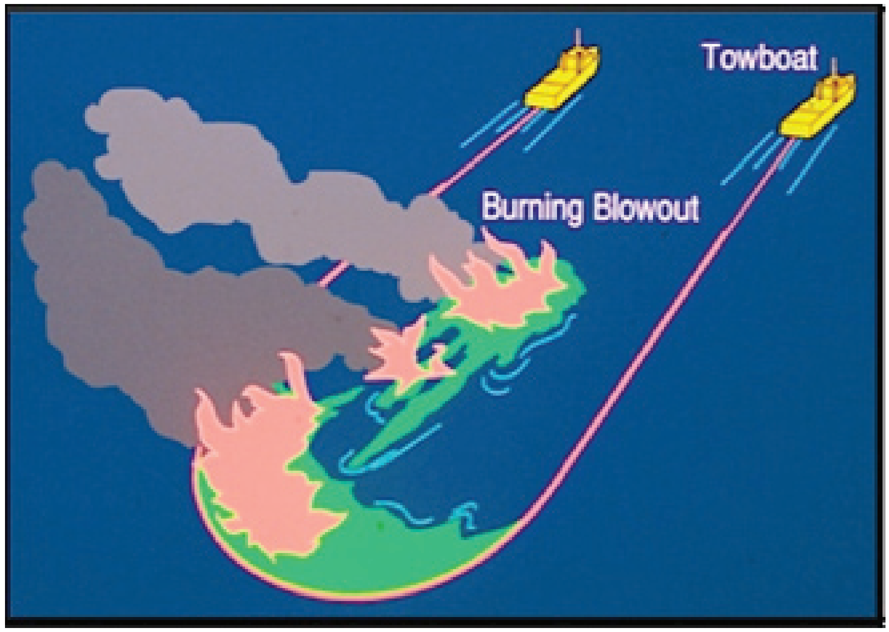


Figure 25: Station-keeping burn mode with blowout.

Strategies for Burning in High Ice Concentrations and New Ice (9-91/0)

Oil in slush-filled leads within areas of almost complete ice cover has been successfully ignited and burned in field trials as shown in Figure 26.

The movement of a continuous layer of new ice or very high concentrations (9/10 or more) of ice over a subsea blowout could theoretically eliminate the effective use of all response options, including in situ burning. In the worst case, the lack of any substantial openings in the ice cover would prevent oil from accumulating to support efficient combustion. In practice, this situation could be improved, in three possible ways: One taking advantage of the natural effects of gas accumulating under the ice, and the other two involving ice management.

1. Large gas accumulations beneath a continuous ice layer will accumulate and likely rupture ice sheets up to three feet thick (Dickins and Buist, 1981). In October, the young ice (often less than 6 inches thick) would likely fracture, break up, and move out from the blowout, rafting and accumulating around the periphery of the blowout plume where burning of the oil and free gas could take place against the ice barrier.

2. A second possible mitigation involves managing the ice through large deflection systems upstream of the blowout as illustrated in Figure 27. Ice deflection is achieved by maintaining a barge or vessel positioned sideways (beam on) to the ice flow with a powerful tug or a vessel with azimuthing

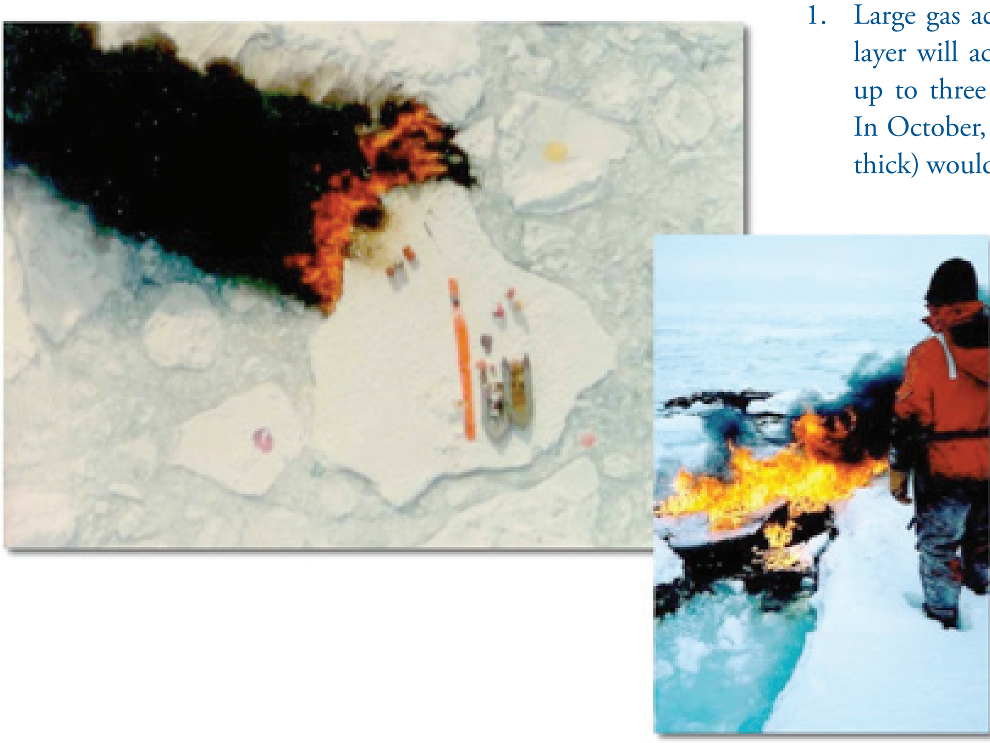


Figure 26: Burning of crude oil bounded by high concentrations of thick ice and slush filled leads during the 1986 Canadian experimental spill in broken ice.

Photos: R. Belore and D. Dickins

drives (such as the Fennica – see Figure 29). Pending the results of full-scale trials, mathematical and ice-tank modeling conducted by Shell to date suggests that the large-scale deflection of ice appears safe and feasible over an ice thickness range from three to six inches as long as the ice cover is not under pressure.

Temporary paths of relatively open water several hundred feet wide could be created downstream of the deflection system to facilitate the continued use of conventional containment and recovery tactics and/or the use of fire boom in a conventional burn mode. As indicated in Figure 27, broken ice along the side and at the apex of the wake also could provide convenient barriers against which wind-herded oil could accumulate to allow in situ burning (see Figure 28). At some point downstream of the deflection barrier (barge or other vessel), the open wake will naturally close due to the overall ice redistribution. With sufficient discharge rate and low enough currents, the oil could reach an equilibrium thickness capable of supporting ongoing combustion of oil within the area influenced by the deflection barrier.

3. Ice management can be used as a means to expose oil trapped under the ice or to modify the ice cover by altering the distribution of floe sizes or by deflecting large floes away from the blowout.

The use of capable icebreakers ice management role is a proven technique that can completely alter the composition of the ice cover and allow continued drilling with moored rigs in heavy ice. In the 1980s, Gulf Canada developed the concept of ice management into a highly evolved operation in maintaining Kulluk on location in often-extreme ice conditions. More recently, the successful 2004 coring program at Latitude 88 degrees north involved two icebreakers (Russian and Swedish) working as a team to maintain a drilling vessel on location for 11 days continuously in high concentrations of 7- to 9-foot-thick multi-year ice. The operation reduced floes drifting toward the drillsite from an initial 3,000 feet or more in diameter to an average ice piece size of 35 to 43 feet by the time they arrived at the drilling location (Keinonen et al., 2006).

In previous ice management operations, the vessels were high ice class but utilized conventional fixed propulsion systems. The current generation of icebreakers employing azimuthing drives (see Figure 29) has demonstrated dramatically enhanced maneuverability in ice compared to the older vessels (literally turning on their own axis in thick ice). By orienting the drives in different combinations, it is possible to efficiently break ice to the side at high speed through the energy imparted by the prop wash carried under the ice. This energy can be used to rapidly fracture and break up the new and young ice, potentially releasing oil that already is trapped beneath the sheet or about to become encapsulated by the rapidly growing ice. Breaking the ice at this stage and using the vessel's prop-wash to flush oil from beneath the ice could expose oil

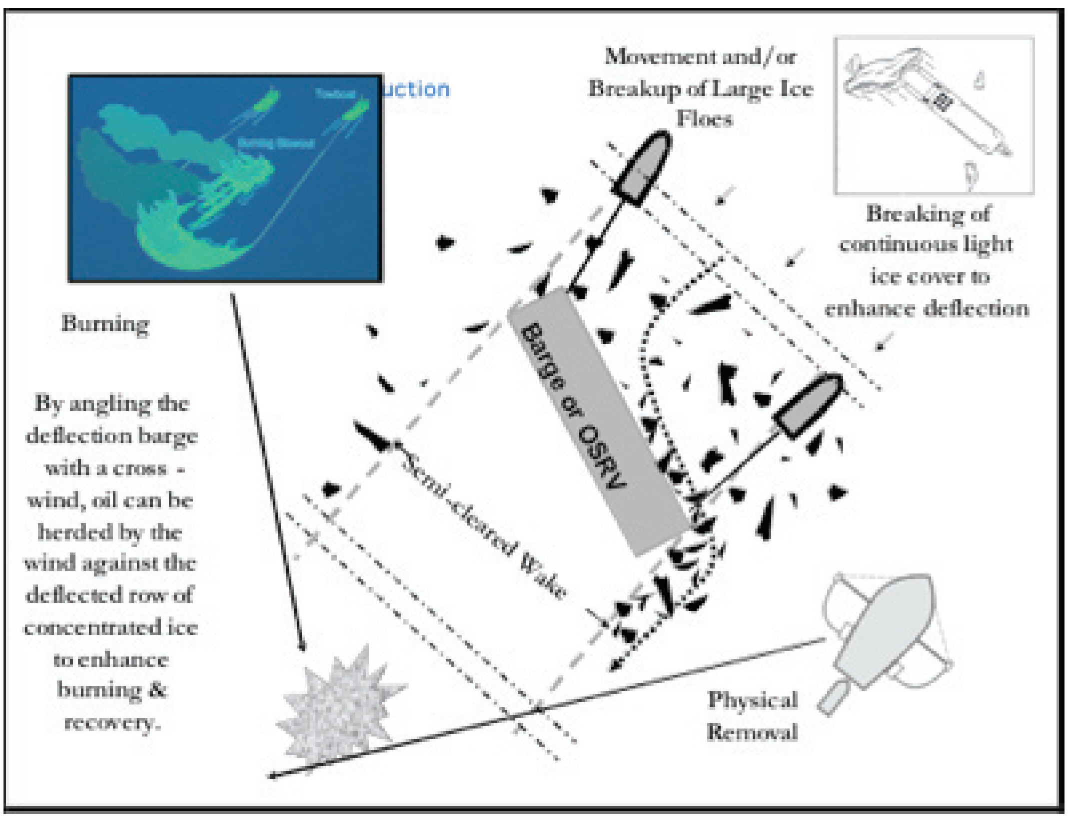


Figure 27: Deflection of light-to-moderate ice concentrations to create a relatively ice-free zone at and down stream of the blowout.

Figure 28: Burning of crude oil wind-herded against a field of broken ice.

Photo: A. Allen

for possible burning on the surface either on or between pieces of broken ice (see Figure 26). A similar procedure could be used to release oil trapped under thicker large floes in lower ice concentrations earlier in the season or during periods of summer ice incursions. In a more pro-active use of ice management, icebreakers could be used well upstream of the blowout to break the larger floes into smaller pieces, or deflect large floes away from the blowout to prevent the accumulation of oil under the ice.

If ice conditions such as active rubble and ridging under pressure make it impossible or impractical to use any form of ice management, oil could surface beneath the continuous or solidly packed ice field where it would quickly become immobilized at the ice/water interface. If left undisturbed, new ice growth (under first-year ice) would soon provide a "lip" around the oil (often within twelve hours to a day, depending upon air temperature and ice thickness) further ensuring that the oil would not spread laterally over a larger area. Typically within 48 hours or less, new ice growth will completely surround the oil, encapsulating, immobilizing and preserving the oil in a fresh state as it drifts with the ice (Norcor 1975; Dickins and Buist 1981).

The primary response options in this situation are to mark and track the encapsulated oil using satellite ice beacons and continue to assess the ice conditions to permit possible deployment of field crews by helicopter (see Figure 30). Using portable equipment such as drills and chainsaws, small groups could safely work on large, thick floes within the pack-ice zone and create access points to expose the oil and burn in situ. As long as safe access is possible with helicopter support, these tactics could be implemented throughout most of the winter months.

In the event that ice conditions preclude safe surface operations, the oiled ice could be tracked until spring (see preceding discussion related to detection and tracking). At that time the trapped oil would become exposed at the surface through brine-channel migration or through surface melt down to the small entrapped oil droplets. Oil exposed through these natural processes has been successfully burned on the surface of solid ice in numerous field trials over the past 30 years (e.g. Norcor 1975; Dickins and Buist 1981; Buist and Dickins 1983; Dickins et al. 2006). In many cases, the oil was exposed for up to one month before being ignited from the ice surface or helicopters (See Figure 31).

Figure 29: Icebreaker Fennica breaking ice through the action of her swiveling thrusters.

Photo: Aker Arctic

Figure 30: Heavy lift helicopter supporting field crews on rough pack ice

Photo: Sakhalin Energy (SEIC)

Figure 31: Burning oil naturally surfaced through ice in the Canadian Beaufort Sea, July 4 1980.

Photo: D. Dickins

CONCLUSIONS

Shell, together with its highly trained primary response contractors, ASRC Energy Services (AES) Response Operations, LLC and Alaska Clean Seas (ACS), has developed one of the most comprehensive oil spill response programs ever assembled for an Arctic exploration program. In the remote event of a major spill, Shell's response team will be ready, on location, to recover and eliminate as much oil as possible, and to minimize environmental impacts.

Conventional open-water recovery systems are capable of dealing with discharge volumes over four times greater than the federally or state mandated WCD in open water (less than 1/10 ice) and potentially at a reduced capacity over a range of open drift conditions (1-6/10) depending on the ice distribution and floe size. In a typical year, these systems are applicable through most of the drilling season from early August to mid-October. In more severe ice concentrations (e.g. drifting floes at break-up, ice incursions in summer and new ice at freeze-up), the recovery effectiveness of mechanical recovery systems (with or without booms) drops sharply to the point where response strategies need to focus on burning to achieve the required oil removal rates.

Controlled burning is a proven Arctic response strategy developed in more than 30 years of experience incorporating extensive lab and tank testing, large-scale field spills and actual incidents. Established guidelines are in place to allow in situ burning to take place with scientifically monitored safeguards to protect responders, the environment and local populations. The physical parameters defining Shell's spill scenarios support the use of burning as an effective response option in any significant ice cover. Key aspects include:

- The fresh nature of oil released to the surface;
- Limited oil spreading due to reduced temperatures;
- Slower weathering rates related to thicker films and lower wave energy;
- A high potential for effective ice containment in any close pack condition; and
- Moderate sea states associated with any significant ice in the vicinity.

At an operational level, by having vessels and critical resources at or near the drilling locations, responders are able to access the oil quickly and implement the most appropriate response strategy according to conditions at the time. The availability of four highly capable support icebreakers, including the latest generation of vessel with azimuthing drives, provides an opportunity to effectively manage the ice for spill response through such measures as ice deflection, flushing trapped oil from beneath small floes, and breaking down large floes to expose oil for burning or recovery.

Important issues and uncertainties affecting the success of a spill response in ice involve the unpredictable and dynamic nature of the offshore environment, and challenges of operating late in the season with freezing temperatures and darkness. Fortunately, at that time the ice acts as an effective containment mechanism, minimizing the contaminated area, and maintaining thick oil films for burning through aerial ignition (reducing the exposure of responders on the surface to extreme conditions). In the case of a late-season incident, proven techniques are available to track oiled ice for extended periods and to take advantage of opportunities to access the oil with helicopter-transported crews as the ice develops.

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OIL SPILL PREVENTION THROUGH RISK MANAGEMENT

BEAUFORT SEA EXPLORATORY DRILLING

Shell Exploration & Production Company

Although the probability of an accidental oil spill from Shell's proposed exploration operations in the Beaufort Sea is extremely low, the potentially serious consequences of any incident must be well understood and mitigated. In order to deal effectively with the risk of an accidental spill, Shell has used its extensive global offshore experience to create one of the most comprehensive spill prevention and control plans ever developed for an exploration program. Shell recognizes that every effort must be made to protect and preserve the offshore and coastal resources of Alaska, including planning and pre-positioning dedicated response equipment. This paper summarizes the spill record and steps taken to ensure that no incidents occur as a result of the proposed exploration drilling in the Alaskan Beaufort. Shell's Regional Exploration Oil Discharge Prevention and Response Plan, submitted to the Minerals Management Service in January 2007, provides full details for prevention and control.

Spill Record

There has never been an oil spill caused by a blowout from offshore exploration and production drilling in state and federal waters off Alaska or in the Canadian Arctic.

The history of offshore operations around the world confirms that large spills are extremely rare events. As reported by the National Academy of Sciences (2003), only 1 percent of the oil discharges in North American waters are related to the extraction of petroleum; and only a fraction of this is from drilling operations. Shell has an excellent record in the Gulf of Mexico for drilling operations. For example, in 2006 the total spill volume was 1.4 barrels, including all reportable spills down to drops of oil capable of producing mere sheens on the water. In 2005, the total spill volume from Shell's facilities was 329 barrels of which 325 barrels were related to a single hurricane Katrina-related incident.

Looking at spill incidents for industry as a whole (exploration and production combined), U.S. OCS platform spill rates have continued to decline since they were first calculated by Stewart (1975), and in subsequent updates by Lanfear & Amstutz (1983), and Anderson & LaBelle (1990, 1994). There were no spills over 1,000 barrels originating from platforms in OCS waters from 1981 to 1999 (Andersen & LaBelle, 2000). Using the USCG classification, there have been no major spills (less than or equal to 2,381 barrels) from U.S. exploration or production platforms since 1973. In the two worst hurricane years with Ivan (2004) and Rita/Katrina (2005), the maximum spills were 1,720 and 2,000 bbl respectively. Historically, the only major spills in the past decade were related to pipeline damage incidents, the worst case discharging 3,200 bbl in 1999.

To help put these incidents in perspective, it is worth noting that approximately 900 new wells are completed in a typical year throughout the Gulf of Mexico region.

Drilling Control

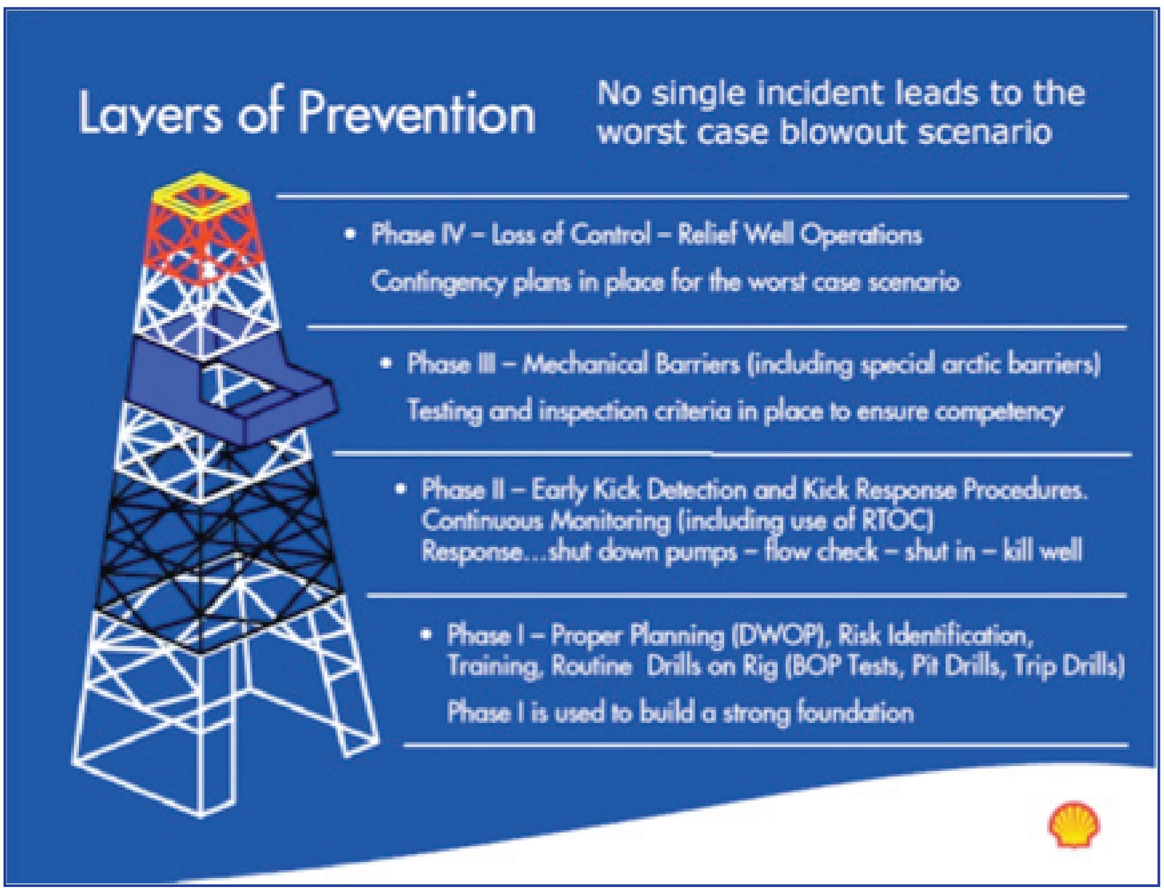
Well control is the process of maintaining positive pressures in the drilled wellbore such that geologic formation pressures do not cause gas or fluids from the formations to escape from the well. Shell believes that no failure of a single barrier, whether caused by operational error or equipment failure, should lead to loss of well control. Therefore, Shell applies the following layers of prevention and containment to maintain well control:

- Layer I includes proper well planning and design through the Drill the Well on Paper (DWOP) process, risk identification, training, and routine tests on the rig (e.g., blowout prevention equipment [BOPE] tests), which build a strong prevention foundation.

- Layer II includes early "kick" detection and timely implementation of kick response procedures. A "kick" means an occurrence where gas or fluids begin to enter the wellbore and well control is challenged. When a kick is detected, the general response is to immediately shut down the pumps, perform a flow check, shut in the well, and kill the well.
- Layer III involves the use of mechanical barriers, including, but not limited to, blowout preventers, casing, and cement. Testing and inspections are performed to ensure competency and integrity.
- Layer IV represents relief well drilling, which would be implemented if a blowout were to occur, despite the first three layers of protection. Contingency plans include dynamic surface control measures and the methods of drilling a relief well.

Well Control During Planning and Preparation (Layer I)

The primary method of well control is properly designed casing/cementing programs to isolate and structurally support downhole formations and maintenance of drilling fluids of sufficient volume and density in the wellbore to counteract any geologic pressures experienced while drilling. Data from previous wells in the area have been used to anticipate formation pressures that might be experienced when drilling the proposed wells, and the wells have been designed to handle the expected pressures. See Figure 1 for an example of this process.



One or more of the following conditions can cause a loss of well control:

- Insufficient fluid weight or volume in the wellbore;
- Fluid losses to the formation;
- Swabbing;
- Shallow gas formations;
- High rate of penetration while drilling a gas sand; or
- Dissolution of shallow gas hydrates.

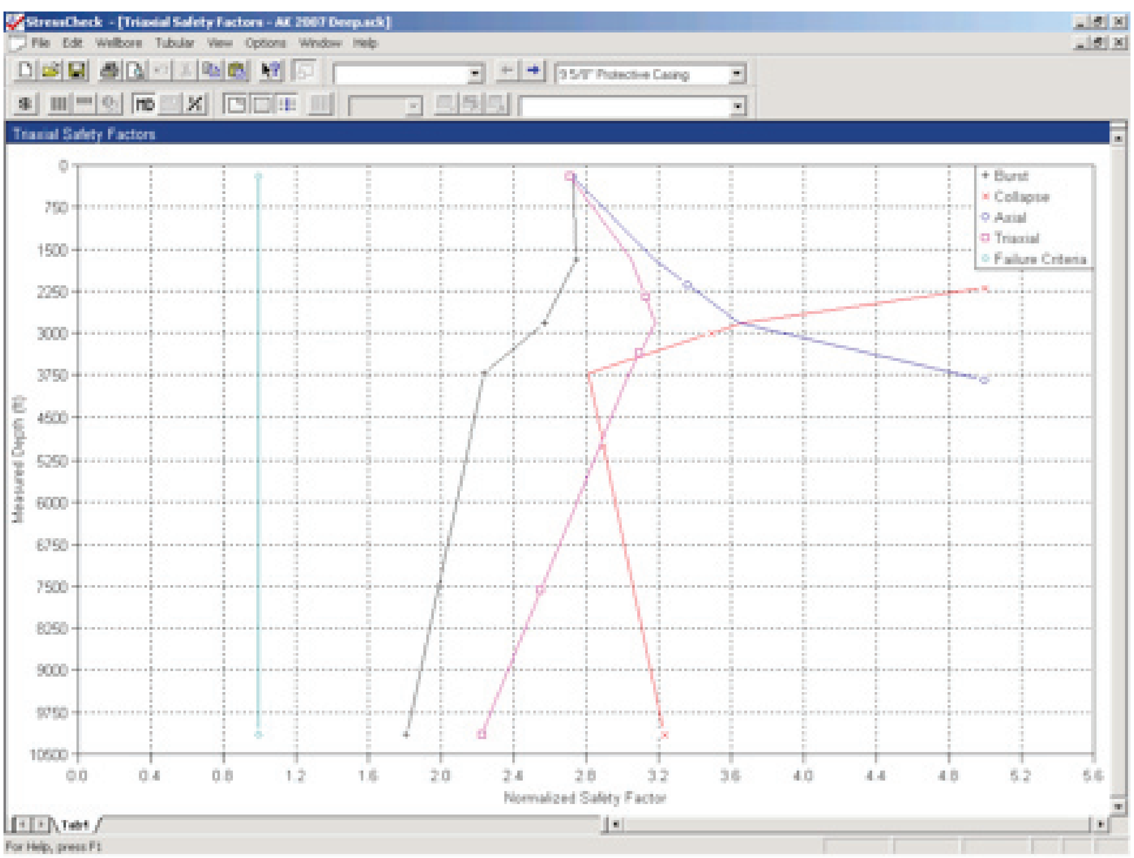
The risk of these conditions occurring is minimized by the proper design of casing strings and drilling fluid systems. To achieve this, Shell's drilling team utilizes best practices consisting of the following procedures:

- Shell's Drill the Well on Paper (DWOP) and Hazard Identification (HAZID) processes to identify risks and apply mitigations;
- Use of industry accepted tools with in-house expert consultation where needed;
- Contingency plans to mitigate any potential causes of loss of well control; and
- Interpretation of available data from seismic operations and neighboring exploration wells, such as rock types and subsurface pressure profiles, to predict downhole pressures and ensure a design for effective control of the well.

The following training and drills support the proactive approach to well control in the well preparation phase:

- Onsite Shell and contractor supervisors maintain current well control certification.
- Prospect-specific well control scenarios and kill techniques are modeled and simulated using Shell's proprietary software and well control simulators at the Robert Training and Conference Center (RTCC).
- Blowout prevention drills performed on a frequent basis ensure the well can be shut in properly and quickly. BOP service and inspection are performed throughout the drilling and off seasons.

MODELS FOR SITE-SPECIFIC WELL CONTROL



RTCC WELL CONTROL SIMULATORS

Well Control During Drilling (Layer II)

The primary means of maintaining well control during drilling utilizes hydrostatic pressure exerted by drilling fluid of sufficient density (weight) to prevent flow of gas or fluids from the formation into the wellbore. The drilling fluid is continuously monitored using both manual and automated methods and can be adjusted as necessary to meet the actual wellbore requirements. Monitored parameters include:

- Mud weight into and out of the well;
- Mud flow rate into and out of the well; and
- Presence and analysis of any gases in the return mud flow.

The latest generation Measurement-While-Drilling (MWD) and Pressure-While-Drilling (PWD) tools are used, allowing real-time monitoring of downhole pressures and drilling parameters. This allows rapid identification of the onset of abnormal pore pressures, swabbing, or the influx of hydrocarbons near the drilling bit. Shell's Real Time Operations Center (RTOC) supports the drilling operations, where technical experts in Houston or New Orleans can assist by monitoring on-going operations, analyzing penetrated formations, and analyzing pressure trends. Data can be transferred from the rig to the RTOC in real-time.

Mechanical and Surface Controls (Layer III)

Once the conductor casing has been set across the shallowest formations, blowout prevention equipment (BOPE) provides a mechanical barrier to loss of well control, key to the third layer of protection. Although rarely needed, this equipment is available as a contingency (secondary to the mud system) to secure the well and safely halt an uncontrolled flow from the wellbore.

In the unlikely event that well control is lost despite these precautions, Shell will immediately mobilize emergency response personnel and equipment. Shell also will consult a well control specialist such as Wild Well Control for the intervention and resolution of a well control emergency. If well control is lost, every effort will be made to regain well control using dynamic surface control measures. Historically, these measures of regaining control have been rapid and effective. Although the specific surface control methods used will depend on the situation, potential mechanical surface control methods include the following:

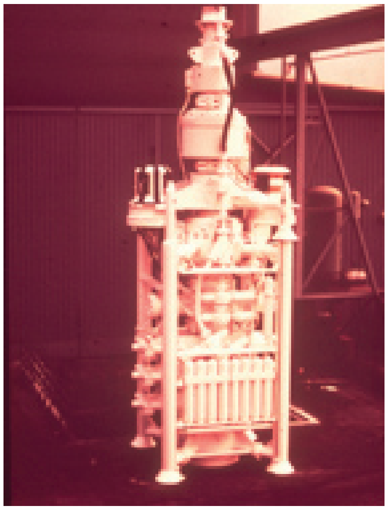
- Natural bridging;
- Pumping mud, plugging material, and/or cement down the well to kill it; and
- Replacing the failed equipment if control was lost due to equipment failure.

Relief Well Control (Layer IV)

A relief well is the fourth layer of the multi-layer well control management system that has proven successful in preventing escalation of a well control incident to a blowout situation. As a precautionary measure, relief well preparation operations are initiated in parallel with surface control methods. Unless it is damaged, the same drilling rig will then commence relief well drilling. Where the original rig is damaged, Shell's second

REAL TIME OPERATIONS CENTER (RTOC)

EXAMPLE OF A BLOWOUT PREVENTERWELL CONTROL



rig will be used to drill the relief well.

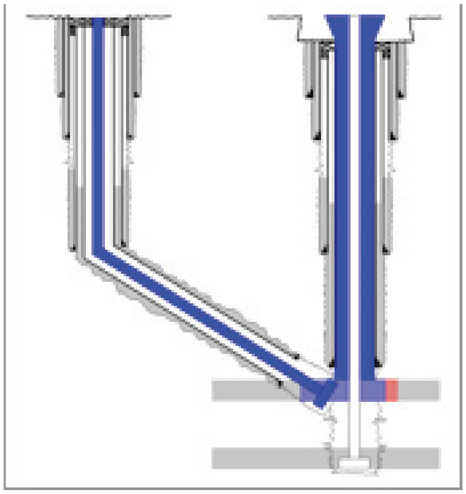
The relief well strategy is to drill a well to intersect the original well. Drilling fluid or cement is then pumped from the relief well to the original wellbore at sufficient rates and weight to stop gas or fluids from flowing into the original wellbore and bringing the well under control. Finally, both wells are properly plugged and abandoned.

A detailed Relief Well Design is submitted to MMS as part of the Application for Permit to Drill. The optimum location for a relief well depends on several factors, including the depth and direction of the wellbore, personnel safety, and weather conditions. The location of the relief well is selected so that it can be drilled in the most efficient manner practicable.

Critical Operations and Curtailment Plan

In addition, stringent adverse weather-drilling restrictions are applied to reduce spill risks related to environmental factors. Shell's Critical Operations and Curtailment Plan, defines procedures to follow when storm or hazardous ice conditions are expected (including continuous weather surveillance). The procedures for ice monitoring include identifying the alert status and conditions of ice movement as well as the site-specific procedures for the support vessels. These procedures are laid out in detailed decision tables linked to "T" times, determining different alert levels in terms of the number of hours predicted before a condition (e.g. weather, ice) may force a curtailment of critical operations.

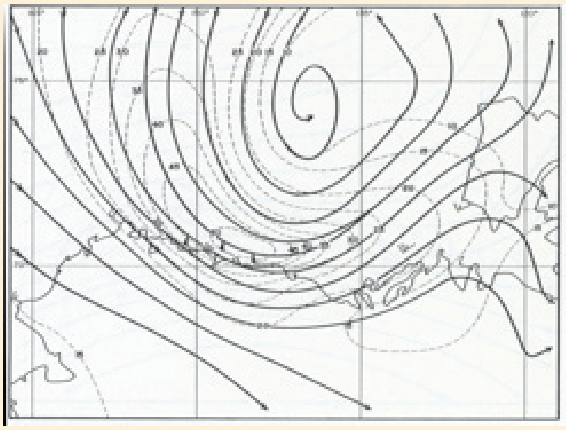
RELIEF WELL DESIGN

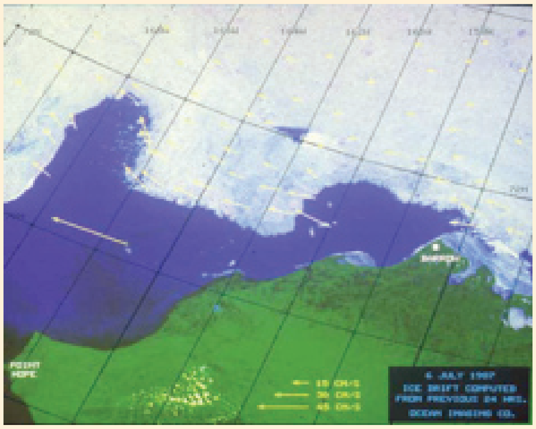


Should it become necessary to cease critical operations, methods will be followed for securing the well and rig, stopping drilling operations, securing the drill pipe and if necessary evacuating the rig. Critical operations will not recommence until the Drilling Manager is satisfied after assessing the residual risks, including:

- Escape, Evacuation and Rescue (EER) system status;
- Weather and ice forecasts;
- Safety of all critical operations: Type, hazards, and the risks involved;
- Availability of additional backup and emergency equipment; and
- Fuel and water sustainability.

ICE FORCASTING





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