ARCTIC RESPONSE TECHNOLOGY
OIL SPILL PREPAREDNESS

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IN SITU BURNING IN ICE-AFFECTED WATERS:

A TECHNOLOGY SUMMARY AND LESSONS FROM KEY EXPERIMENTS

FINAL REPORT 7.1.2
Report from Joint Industry Programme on relevant scientific studies and laboratory and field experiments on the use of in-situ burning in ice-affected offshore environments

ABOUT THE JIP

Over the past four decades, the oil and gas industry has made significant advances in being able to detect, contain and clean up spills in Arctic environments. To further build on existing research, increase understanding of potential impacts of oil on the Arctic marine environment, and improve the technologies and methodologies for oil spill response, in January 2012, the international oil and gas industry launched a collaborative four-year effort – the **Arctic Oil Spill Response Technology Joint Industry Programme (JIP)**.

Over the course of the programme, the JIP will carry out a series of advanced research projects on six key areas: dispersants, environmental effects, trajectory modeling, remote sensing, mechanical recovery and in situ burning. Expert technical working groups for each project are populated by the top researchers from each of the member companies.

JIP MEMBERS

The JIP is managed under the auspices of the International Association of Oil and Gas Producers (OGP) and is supported by nine international oil and gas companies – BP, Chevron, ConocoPhillips, Eni, ExxonMobil, North Caspian Operating Company (NCOC), Shell, Statoil, and Total – making it the largest pan-industry programme dedicated to this area of research and development.

EXECUTIVE SUMMARY

This report summarizes relevant scientific studies and laboratory and field experiments on the use of in situ burning (ISB) in ice-affected offshore environments. ISB refers to the controlled burning of oil spilled from a vessel, facility, platform, or pipeline close to where the spill occurred. Although ISB has been successfully used to respond to spills on land, this report focuses on the response to marine oil spills in the Arctic environment. The intended audience is industry management, contingency planners, and responders who want to familiarize themselves with the background on Arctic ISB science, technology, and related research and development. The report highlights key findings, conclusions, and key references.

ISB has been considered a primary spill response option for oil spills in ice-affected waters from the start of offshore drilling in the Beaufort Sea in the 1970s. Field trials at that time demonstrated on-ice burning of spilled oil offered the potential to remove almost all of the oil present on an ice surface with only minimal residue. Since then, a great many studies and trials have been undertaken to investigate and document burning of crude oil slicks (both fresh and emulsified) in cold open water, slush ice, drift ice, pack ice and on solid ice. These are summarized in the report. The laboratory and field experiments spanning the past 40+ years have led to a good understanding of the science of burning in a wide variety of ice conditions and the importance of such factors as minimum ignitable slick thickness for various oil types and states of weathering, wind and wave limits for successful burning, and the maximum water, ice and snow contents that can be tolerated for a successful burn.

Controlled ISB has proved effective for oil spills in ice and has been used successfully to remove oil from spills in ice-affected waters from storage tank, and ship accidents in Alaska, Canada and Scandinavia since the 1970s. ISB is a response option that has rarely been used on open water marine oil spills, but its successful use during the Gulf of Mexico (GOM) Deepwater Horizon (DWH), (Macondo) response has generated considerable interest. Between April 28th and July 19th, 2010, over 400 burns were initiated and resulted in the removal of between 220,000 and 310,000 bbls of oil (USCG, 2011; Mabile 2012). A section of this report discusses how many of the lessons learned from this effort can be applied to ISB in Arctic open water conditions as well.

Research and development on equipment for ISB in ice-affected waters is also presented in this report and covers ignition systems, fire-resistant booms, and herders. The history of each technology is reviewed.

ISB removes surface oil generating a plume of combustion gases that is propelled into the atmosphere by the heat of the fire where it is rapidly dispersed by the wind. The hazards from smoke can be mitigated by maintaining prescribed separation distances from sensitive downwind areas.

The key messages in this report are:

1. *There is sufficient information from laboratory, test tank and field trials to understand the basic principles of burning oil in wide variety of snow and ice conditions.*
2. *The technology exists today to conduct controlled in situ burns of oil spilled in a wide variety of ice conditions, and*
3. *Most of the perceived risks associated with burning are easily mitigated by following approved procedures and maintaining appropriate separation distances.*

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GLOSSARY OF KEY TERMS

Ambient Conditions are those in an environment, such as ambient temperature, humidity, etc. For example, if an oil slick is at or above the temperature of its flash point, the slick will ignite rapidly and easily. If the ambient temperature is below the flash point for the spilled oil, the slick may be difficult to ignite.

Barrel (bbl) is equal to 42 United States gallons at 15.5°C.

Biodegradation is the process where naturally occurring bacteria and other micro-organisms consume hydrocarbons as a food source.

Booms are floating barriers used for the collection, diversion, deflection, and containment of spreading liquids.

Brash Ice is defined as accumulations of floating ice fragments not more than 2 m across. Brash ice is common between colliding floes or in regions where pressure ridges have collapsed.

Broken Ice is an older term used to describe an ice sheet that is not continuous. It has been replaced by the more descriptive terms pack ice, drift ice, etc.

Burning Agents means those additives which, through physical or chemical means, improve the combustibility of materials to which they are applied.

Burn Efficiency is usually expressed as the percent reduction in original oil weight following combustion. It is a function of three main factors: initial slick thickness, thickness of residue at the extinction of a burn, and the aerial coverage of flames.

Burn Residue is the unburned oil or incomplete combustion products remaining on a land, water, snow or ice surface when a fire extinguishes. Residues can range from brittle to stiff, taffy-like material.

Carbon Monoxide (CO) is a common by-product of incomplete combustion.

Centipoise (cP) a unit of measurement for dynamic viscosity.

Centistoke (cSt) a unit of measurement for kinematic viscosity.

Combustion By-Products include the smoke plume constituents and any incomplete burn combustion products remaining after a burn is extinguished (residue).

Containment is the use of boom, herding agents, natural barriers on land, or ice, to constrain and/or concentrate an oil slick.

Controlled Burn is combustion that is started and stopped by human intervention.

Effectiveness / Efficacy is the ability to produce the desired outcome.

Emulsion, for spill response purposes, is the suspension of water in an oil slick which then alters its appearance, behaviour, fate, and impacts recovery and treatment options. Water-in-oil emulsions may contain 20%-80% water. Emulsions may be temporary or permanent.

Emulsion Breaker is an emulsion treating agent that separates the oil and water phases.

Evaporation is the preferential transfer of light- and medium-weight components of oil from the liquid phase to the vapour phase. Evaporation is typically the most dominant weathering process (oil type and spill location dependent).

Encapsulation is the process of oil on the underside of a growing ice sheet being enclosed into the ice by the downward growth of ice crystals.

Fire Point is the temperature of a fuel at which it will continue to burn for at least 5 seconds after ignition by an open flame.

Fire Diameter is the horizontal distance from one side of a fire to the opposite side, through the centre of the fire.

Flash Point is the lowest temperature at which the vapour of a flammable liquid will ignite in air. The flash point is generally lower than the temperature needed for the liquid itself to ignite. A substance may ignite briefly, but vapour may not be produced at a rate to sustain a fire. In general a fire point can be assumed to be about 10ºC higher than flash point for a given material.

Frazil Ice is a collection of loose, randomly oriented needle-shaped ice crystals in water. It resembles slush and has the appearance of being slightly oily when seen on water. It usually forms in rivers, lakes and oceans, on clear nights when air temperatures reach –6°C or lower. Frazil ice is the first stage in formation of sea ice.

Fresh / Freshwater is a classification of water body by its low salinity, usually at less than 0.5 parts per thousand (ppt).

Gelling Agent is a chemical thickener which, when mixed with oil, turns the mixture into a solid or gel.

Gelled Gasoline is a gasoline/diesel mixture formed by adding a gelling agent to gasoline. Gelling agents include aluminium soaps, wax, tallow, etc.

Heat Flux is the total amount of heat radiated, convected and conducted away from a fire per unit time.

Herding Agent is a product which contracts a liquid (in this case an oil slick) on a water surface by exerting a higher spreading pressure than the oil slick.

Ice-affected waters are those that have ice in some form on their surface.

Ignition Sources/Igniters are devices designed to provide a heat source to a material and increase its temperature to Fire Point. Commonly used ignition devices include propane or butane torches, gelled fuel with an attached flare, diesel-soaked rags or sorbents, helicopter-slung gelled fuel (Heli-torch), and road flares.

Ignitable Thickness means in general, the thickness of oil necessary to generate sufficient vapours to enable ignition.

In Situ Burning (ISB) is the controlled combustion/burning of spilled oil in place such that the petroleum hydrocarbons are predominantly converted to CO2 and water which are released to the atmosphere. See also Controlled Burning.

Interfacial Tension is the tendency of a liquid surface, in contact with an immiscible liquid, to contract. The imbalance of forces at the liquid:liquid interface is due to the difference in molecular forces in the two immiscible liquids.

Marine or Salt water is a classification of water body based on salinity. It is sometimes used synonymously with ocean, but reflects a broader salinity range of 30 parts per thousand and above.

Natural Dispersion is the process of breaking waves forcing oil droplets into the water column, which can result in at least a portion of the droplets small enough to remain in the water.

Nitrogen Dioxide (NO2) is a gaseous by-product of oil combustion.

Oil means oil of any kind of petroleum hydrocarbon, in particular those in liquid form which could be spilled.

Particulates are very small pieces of solid materials (e.g., dusts, soot, fumes) or liquid material (mists, fogs, sprays) suspended in the air.

Particulate Matter refers to particulates with a size range judged to be easily inhaled and can enter human lungs (10 micrometres in diameter or smaller). Particulate matter is often grouped into two categories:

1. PM 10 is a coarser mixture of solid and liquid droplets (0 to 10 microns in diameter), and
2. PM 2.5 is the particles less than 2.5 micrometres in diameter, called "fine" particles. These particles can penetrate deeply into human lungs.

Polycyclic Aromatic Hydrocarbons (PAHs) are a group of hydrocarbons compounds characterised by multiple benzene rings, very low vapour pressures, and relatively low flammability (compared to other compounds found in crude oils). PAHs are found in unburned oils, burn residue, as well as in the smoke from a burn.

Primers, also known as Ignition Promoters, are substances (usually combustible liquids) which enable flames to spread across the surface of a slick that otherwise flames would not naturally spread.

Promoters, also known as Combustion or Burn Promoters, are substances (often sorbent-like solids or powders, or wicking agents) which promote more efficient removal of hard-to-burn slicks by their wicking action and/or insulating a slick from cooler underlying water.

Sheen is a very thin layer of spilled oil, less than 0.0003mm in thickness. Sheen may appear as silver (0.00007 mm), rainbow (0.00015 mm) or grey (0.001 mm), depending on thickness, sheens range in colour from dull brown for the thickest sheens to rainbow, greys, silver, and near-transparency in the case of the thinnest sheens.

Slick is a thin layer of spilled oil on water.

Spreading is a dominant transport process for most oil spills, whether on water, on land, or in ice/snow. Spreading occurs due to surface tension and gravity.

Spreading Pressure is the net interfacial force exerted by an oil lense floating on water. If the spreading pressure is positive, the oil will spread to sheen: if it is negative the oil will contract and thicken.

Surface Collecting Agent is another term for herding agent.

Surfactant, also referred to as surface-active agents, is a chemical which contains both an oil-soluble and water-soluble components and can reduce the interfacial tension and/or surface tension of another liquid.

Viscosity is the resistance to flow of a liquid and may be reported in one of two ways for oil spills. Dynamic viscosity (μ) refers to internal friction of a substance (e.g., oil), is a function of oil type, emulsion water content and temperature, and is measured in Centipoise units (cP). The lower the viscosity, the thinner the fluid (e.g., water = 1 cP, molasses = 100,000 cP). Kinematic viscosity (v) is a given fluid's dynamic viscosity divided by its density, is measured in Stoke (St) units, and is often reported in centistokes (cSt). Since the density of oil is not too different from water, rough estimates, of dynamic and kinematic viscosity are similar.

Weathering is the process of alteration of physical and chemical properties of a material through natural processes, including spreading, evaporation, dissolution, photo-oxidation, emulsification, sedimentation, and biodegradation.

Window-of-Opportunity is an interval of time during which conditions are favourable and an opportunity exists for a spill response option to be implemented effectively.

CHAPTER 1. INTRODUCTION

The objective of this report is to summarize major scientific studies, experiments, and case studies on the use of in situ burning (ISB) in ice-affected offshore environments. ISB refers to the controlled burning of oil spilled from a vessel, facility, or pipeline close to where the spill occurred. Although ISB can be used to respond to spills on land and shorelines, the focus here is on the response to offshore marine oil spills in the Arctic environment.

The intended audience is industry management, contingency planners, and responders who want to familiarize themselves with the background on Arctic ISB science, technology, and related research and development. The report highlights key findings, conclusions, and key references.

ISB is not a new technique, having been researched and used for a variety of oil spills since the early 1970s. In general, the technique has proved to be effective for oil spills in ice conditions and has been used successfully to remove oil spilled in ice-covered waters resulting from storage tank and ship accidents in Alaska, Canada, and Scandinavia. Although there have been several incidents of vessel oil spills that inadvertently caught fire, intentional ignition of oil slicks on open water has only been seriously considered since the development of fire-resistant boom beginning in the early 1980s.

Added interest in burning of spills on water has also developed as a result of research in the mid-1980s that suggested that large spills on water could be ignited via aerially-deployed igniters and successfully burned without the use of containment boom. The theory is that if ignited soon enough, thick slicks of burning oil should remain thick enough for burning because of the natural herding action of the strong air currents drawn into the burning slick zone to feed the fire. This phenomenon was observed repeatedly during burns conducted following the DWH incident in the GOM (Allen *et al.,* 2011).

1.1 Advantages and Operational Issues Associated with In Situ Burning

The decision to employ ISB involves trade-offs between the benefits of using burning to remove oil from the water or ice surface and the potential effects of burning. In most cases for spills in ice-covered waters, the benefits far outweigh the potential detrimental effects. The following are some of the key advantages and operational issues that should be considered in the use of ISB as an oil spill countermeasures tool. In subsequent chapters of the report, details supporting the following statements are presented.

- **Simple Logistics:** ISB of thick, fresh slicks can be initiated very quickly by igniting the oil with devices as simple as an oil-soaked sorbent pad. Ice can provide natural containment of spilled oil, keeping the slick thick and slowing weathering processes for extended periods of time; thus, allowing oil burning operations to proceed with only helicopters and igniters. The use of towed fire-resistant boom, even in light drift ice, to capture, thicken, and isolate a portion of a spill is far less complex than the traditional operations involved in recovery, transfer, storage, treatment, and disposal. The *DWH* ISB operations involved less than 100 people, 30 vessels (mostly vessels of opportunity), two aircraft, 23,000 feet of fire boom, and 1,700 igniters to remove between 220,000 and 310,000 barrels (bbls) of oil (USCG, 2011; Mabile 2012). The logistics are particularly favourable when compared with the use of traditional containment and recovery techniques, and the attendant problems with dealing with vast amounts of recovered oil, water, and emulsion.

- **High Elimination Rates:** The burning rate of thick slicks of oil has been measured to be in the range of 3.5 mm/minute. During the *Deepwater Horizon* response it was estimated that ISB removed almost twice the amount removed by skimming (USCG, 2011), including burning 50,000 to 70,000 bbls on one day alone. Each burn removed between 600 and 850 bbls of oil at a rate averaging 700 to 800 bbl/h. One single 12-hour burn removed an estimated 6,000 to 8,300 bbls of oil (Mabile, 2012).
- **High Efficiency of Burn:** The volume of oil eliminated depends on the original thickness of oil, which is commonly burned to a thickness ranging from 1 to 10 millimetres depending on the type of oil burning. Burning oil layers of about 100 millimetres or more can thus result in an efficiency of removal of 90 to 99 percent.
- **Versatility:** ISB can be used on fresh water or salt water; on lakes, streams, and oceans; onshore; or on wetlands/marshes with only a few centimetres of water. Burning can be used in ice covers from trace to 9+/10ths; in snow; on calm water; and in seas approaching a Beaufort scale wind force of 3 to 4. The burning of spilled oil can be used under tropical and Arctic conditions and is particularly effective in ice and snow conditions.
- **Cost:** Based on comparable spill events and volume removal rates, the cost of controlled burning is likely to be substantially less than that of physical recovery, and the use of chemical dispersants.
- **Fire Control:** If oil on water is at a temperature near or above its flash point, ignition of the oil will result in very rapid spreading of the flame. In cases where a large amount of volatile oil is spilled, a cloud of vapours can collect near the source in calm wind conditions and may represent a significant flash-back and/or explosion hazard. In such cases, care must be taken to isolate the portion of the slick to be burned from the source of spillage and from other areas of the slick.
- **Combustion By-products:** ISB produces a dense, black plume of smoke rising from the fire. At low wind speeds and in stable atmospheric conditions the plume can rise several hundreds of metres into the air before levelling off. The plume is slowly dispersed by wind and is usually visible within a few kilometres of the burn site. Burn residue is the material that remains on a surface after an in situ burn extinguishes. The residue is generally depleted of lighter petroleum constituents, and it contains elevated concentrations of heavier compounds.

1.2 Report Outline

The report begins in **Chapter 2** with a review of the basics of ISB of oil on water, including the requirements for effectively igniting and burning an oil slick on water, likely rates and efficiencies, and the effects of such factors as emulsification and the presence of ice. **Chapter 3** summarizes the major experimental programmes, with particular emphasis on field experiments in ice that advanced the science of ISB and the associated technologies for its effective use. **Chapter 4** contains a summary of the lessons learned from the in situ burn operations during the DWH response in the GOM in 2010 and how they can be applied to burning in ice-affected waters.

CHAPTER 2. FUNDAMENTALS OF IN SITU BURNING ON WATER

This chapter summarizes how oil burns on water: the requirements for effectively igniting and burning an oil slick on water, likely rates and efficiencies, and the effects of such factors as emulsification and the presence of ice.

2.1 Requirements for Ignition

To burn spilled oil, three elements must be present for ignition: fuel, oxygen, and a source of ignition. The oil must be heated to a temperature at which sufficient hydrocarbons are vaporized to support combustion in the air above the slick: it is the hydrocarbon vapours above the slick that burn, not the liquid itself. The temperature at which a slick produces vapours at a sufficient rate to ignite is called the Flash Point. The Fire Point is the temperature, a few degrees above the Flash Point, at which the oil is warm enough to supply vapours at a rate sufficient to support continuous burning.

2.1.1 Heat Transfer to Slick

Figure 2-1 (next page) illustrates the heat transfer processes of a typical in situ burn on water or ice. The rising column of combustion gases carries most heat away from the burn, but a small percentage (about 3%) radiates from the flame back to the surface of the slick. This heat is partially used to vaporize more liquid hydrocarbons to rise and mix with the air above a slick and burn, while a small amount transfers into the slick and eventually to the underlying water. A burning oil slick reaches a steady state when the vaporisation rate sustains combustion, which radiates heat back to the slick surface to continue vaporisation. This ‘balance’ holds until there is insufficient fuel for vaporisation to sustain combustion and a burn extinguishes.

2.1.2 Flame Temperatures and Total Heat Flux

Flame temperature and total heat flux relate to how fast and efficiently a slick will burn and the safe approach distances to large oil fires. Flame temperatures for crude oil burns on still water are about 900° to 1,200°C. But the temperature at an oil slick/water interface is never more than the boiling point of water and is usually around ambient temperature. There is a steep temperature gradient across the top layer of a burning slick. The oil surface is very hot (350° to 500°C), yet the oil just beneath it is near ambient temperature. Total heat flux generated by an oil pool fire can be in the range of 100 to 250 kW/m^2. The higher heat flux is associated with windy conditions that promote a more complete combustion.

2.1.3 Importance of Slick Thickness

The key parameter for whether or not an oil slick will burn is slick thickness. If a slick on water is thick enough, it acts as insulation and keeps the burning slick surface at a high temperature by reducing heat loss to underlying water. This layer of hot oil is called the "*hot zone*". As a slick thins, increasingly more heat is passed through it, and eventually enough heat is transferred to drop the temperature of its surface below its Fire Point, at which time the burning stops. The

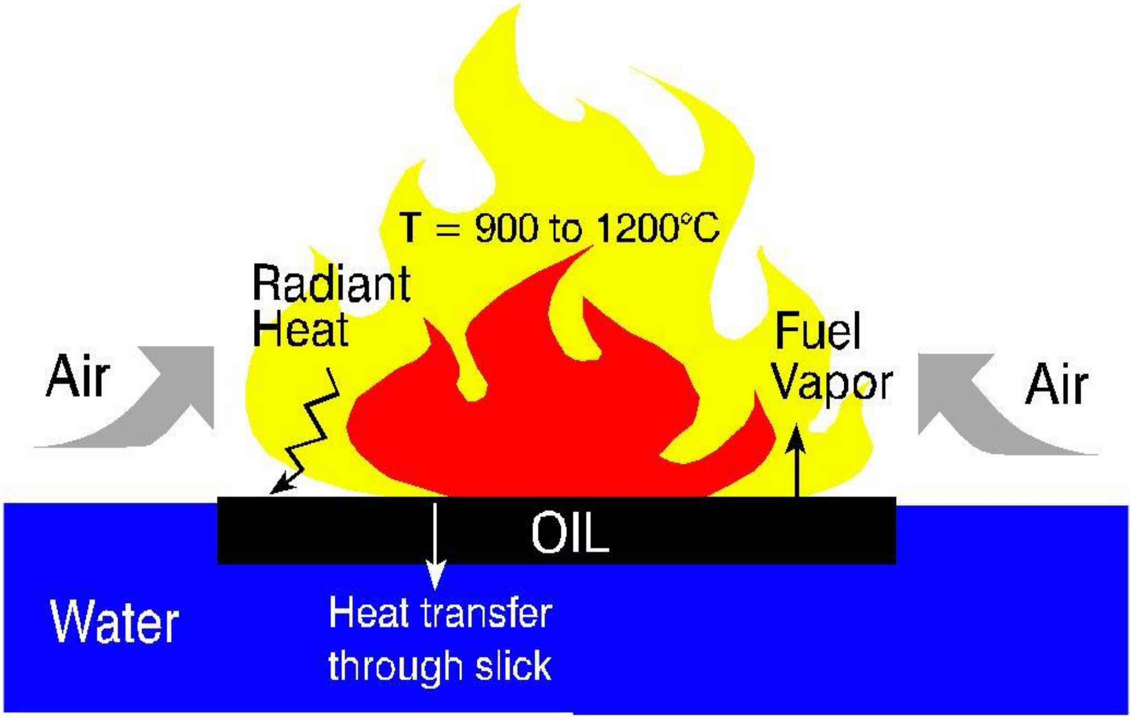

Figure 2-1 Basic heat and mass transfer processes that control in situ burning (source: SL Ross Environmental Research)

minimum ignitable thickness for fresh crude oil on water is about 1 mm. Minimum ignitable thicknesses are greater for aged, unemulsified crude oils and diesel fuels (about 2 to 5 mm), and residual fuel oils, such as IFO 380 (aka Bunker "C" or No. 6 fuel oil) and emulsions (about 10 mm).

2.1.4 The Vigorous Burning Phase

In the final stages of burning, the "hot zone" approaches the water surface as a slick thins. The temperature of water directly beneath a slick, when no longer insulated by a thicker slick, increases. For slicks on calm water with little or no current, as may be the case in drifting pack ice or on melt pools, the temperature of underlying water can increase to the boiling point. When water begins to boil, steam vigorously mixes the remaining oil and ejects oil droplets into the flames (**Figure 2-2**; next page). This causes an increased burn rate, flame height, radiative heat output, and foaming (particularly with emulsified oils), which is called the vigorous burning phase. This phenomenon has been observed in burns of oil on melt pools on sea ice in spring, but never when using a towed boom, probably because the water beneath the slick in the latter case does not stay there long enough to boil.

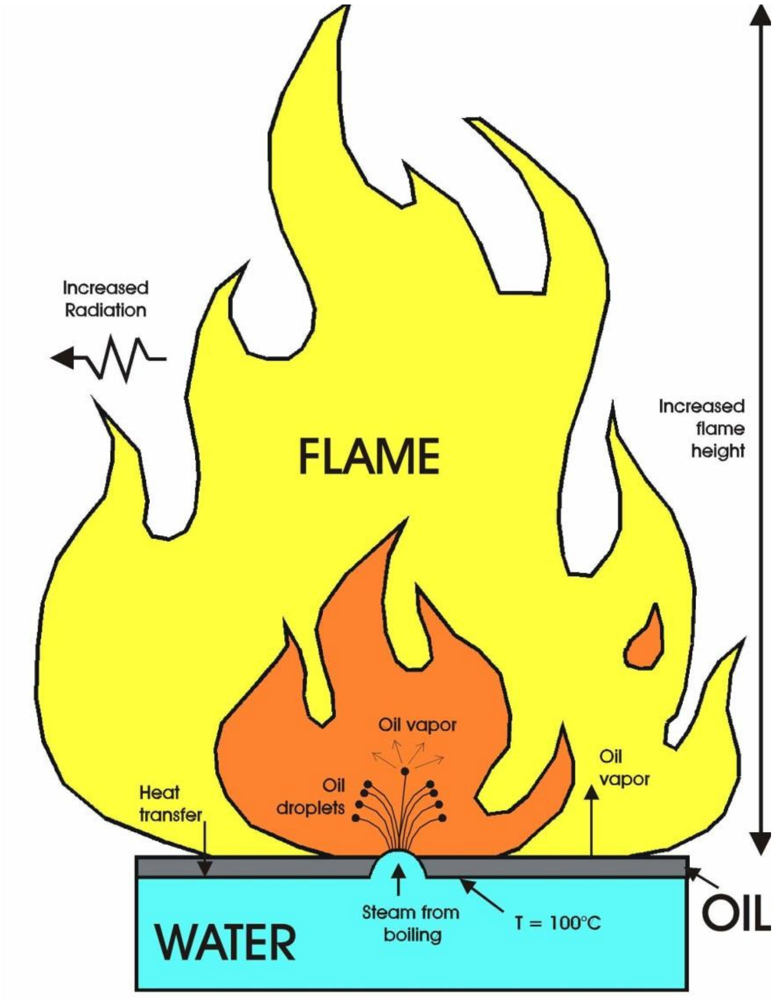

Figure 2-2 The vigorous burning phase (source: SL Ross Environmental Research)

2.1.5 Secondary Factors Affecting Ignition

Aside from oil type and thickness, other factors which can affect the ignitability of oil slicks on water include: wind speed, emulsification of an oil, and igniter strength. The maximum wind speed for successful ignition of large burns is 10 to 12 m/s (20 to 24 knots). For weathered crude that has formed a stable water-in-oil emulsion, the upper limit for successful ignition is about 25% water. Some crudes form meso-stable emulsions which can be easily ignited at much higher water contents. For example, paraffinic crudes appear to be in this category.

Other factors affecting ignitability include ambient temperature and waves. If the ambient temperature is above an oil's flash point, that slick will ignite rapidly and easily and flames will spread quickly over the slick surface. Flames spread more slowly over oil slicks at sub-Flash Point temperatures. The presence of waves can prevent the ignition of marginally ignitable slicks by reducing the surface temperature of the oil slick by mixing it.

2.2 Flame Spreading

Flame spreading is a crucial aspect of effective ISB. If flame does not spread to a large part of the slick surface, then overall removal efficiency will be low. There are two ways in which flames spread across a pool of liquid fuel: radiant heating of adjacent liquid oil warms it to its fire point; and hot liquid beneath flame spreads over surrounding cold fuel, carrying the flames with it.

As oil evaporation (or weathering) increases, the flame spreading velocity decreases; as the difference between ambient temperature and an oil's flash point increases, additional heating of the slick for ignition is required. Flame spreading velocities increase with increasing slick thickness due to the insulating effect of the oil layer. For a constant slick thickness and flash point, increasing viscosity reduces flame-spreading velocity. Downwind flame spreading increases with increasing wind speed. This is likely due to the bending of flames by wind enhancing heating of a slick. Flames tend to spread straight downwind from an ignition point without significant crosswind spread (**Figure 2-3**). Flame spreading upwind is slow, although the presence of a barrier or ice edge that provides a windbreak can permit rapid upwind or crosswind spreading. Slow upwind spreading of flames is one method of fire control. In general, ignition of an oil slick should take place along the upwind edge of a slick. The presence of water currents and regular waves (or swell) does not seem to affect flame spreading for unemulsified oils, but choppy or steep waves have been noted to curtail flame spreading over emulsions. See the synopsis of emulsified oils in **Section 2.5**.

Figure 2-3 Flame spreading in wind (photo source: Dome Petroleum)

2.3 Oil Burning Rates

The rate at which an in situ burn consumes oil is generally reported in units of slick thickness removed by combustion per unit time (mm/min is the most commonly used unit). This removal rate is a function of fire size (diameter), slick thickness, oil type, and ambient environmental conditions. For most large fires, > 3 m diameter (fires greater than this diameter are turbulent – smaller fires are laminar and burn slower) of unemulsified crude oil on water, the rule-of-thumb is 3.5 mm/min. Automotive diesel and jet fuel fires on water burn at a slightly higher rate of about 4 mm/min.

Table 2-1 summarizes some rules-of-thumb for in situ burning removal rates.

Table 2-1 Summary of in situ burning rates for unemulsified oil spilled on water

Oil Type/Condition	Burn/Removal Rate[+]
Gasoline >10 mm thick	4.5 mm/min
Distillate Fuels (diesel and kerosene) >10 mm thick	4.0 mm/min
Crude Oil >10 mm (0.4 inches) thick	3.5 mm/min
Heavy Residual Fuels >10 mm thick	2.0 mm/min
Slick 5 mm thick*	90 percent of rate stated above
Slick 2 mm thick*	50 percent of rate stated above

[+] Estimates of burn/removal rate are based on experimental burns and should be accurate to within ±20 percent.
* Thin slicks will naturally extinguish, so this reduction in burn rate only applies at the end of a burn.

2.4 Flame Heights

The thick, black smoke produced during combustion can obscure flames from larger oil fires making it difficult to accurately estimate flame heights. The best available information suggests the following rules-of-thumb:

- For fires having diameters less than 10 m, flame heights are twice the fire diameter, and
- For larger fires, the ratio declines, approaching a value of one for very large fires.

2.5 Factors Affecting Residue Amounts and Burn Efficiency

Oil removal efficiency by ISB is a function of two main factors: the thickness of the slick (initial and final) and the areal extent of flames. Secondary factors include conditions such as wind and current which could push, or herd, slicks against ice edges or booms, and oil weathering.

Wind and current can push a slick against a barrier, such as an ice edge, thus thickening that oil for burning. As little as a 2 m/s (4-knot) wind is capable of holding oil against a barrier at thicknesses that sustain combustion. Indeed, the concept of uncontained burning is based on the ability of a self-induced wind (drawn in by the combustion and its rising column of hot gases), to keep an uncontained slick at burnable thicknesses. This phenomenon was observed repeatedly during burns conducted during the DWH incident in the GOM.

Water current can dramatically increase burning efficiency (i.e., reduce the amount of burn residue) by herding burning oil against a barrier. The detrimental effects of current can include: 1) entrainment of residue beneath an ice edge or boom as the residue density and viscosity increase during a burn, and 2) over-washing a burning slick causing extinction of flames. Steep, choppy waves can also have a negative effect on the burning process.

Residue from a typical, efficient (>85%) in situ burn of crude oil up to 40 mm thick (typical thicknesses for oil pools in ice) is a 1 mm thick semi-solid, tar-like layer with an appearance similar to the skin on an old, poorly-sealed can of paint that has congealed. For thicker slicks (40 to 100 mm), residue thicknesses are in the range of 3 to 5 mm. For the thickest slicks (about 150 to 300 mm; typical of what might be expected in a towed fire boom), the residue can be a solid. Cooled residue from efficient burns of thick (e.g., >100 mm), heavier crude oils could be dense enough to sink.

Physical properties of burn residues depend on burn efficiency and oil type. Efficient burns of heavier crudes generate brittle, solid residues (like peanut brittle). Residues from efficient burns of other crudes are described as semi-solid (like cold roofing tar). Even if the residues from these burns could be thickened again, they are extremely difficult to reignite.

Inefficient burns generate mixtures of unburned oil, soot, and burned residues that are sticky, taffy-like, or even liquid. Burns of light distilled fuels result in a residue that is similar to the original fuel but contains precipitated soot. If this type of residue can be thickened again, it might be possible to reignite.

Burning operations during the DWH incident produced a floating residue that was stiff and tar-like when it cooled. These residues could not be reignited.

2.6 Effects of Emulsification

Although the formation of water-in-oil emulsions is not as predominant a weathering process with spills in ice as it is for spills in open water, emulsions could be formed in some situations. Emulsification of an oil slick negatively affects ignition and burning. Emulsion water contents are typically 60 to 80% with some as high as 90%. The oil in an emulsion cannot reach a temperature higher than 100°C until its water is either boiled off or removed. The heat from igniters or adjacent burning oil frequently boils the water rather than heat emulsified oil to its fire point. Although there are some variations with oil type, there is little change from unemulsified oils in overall burn efficiency with emulsions having water contents up to about 12.5%; stable emulsions with water contents above 25% are generally very difficult to ignite and burn with any significant effectiveness. For unstable emulsions, burn rates decline significantly with increasing water content. **Table 2-2** shows the predicted decrease in burn rate for increasing water content in unstable emulsions for fires >3.5 m diameter.

Table 2-2 Predicted oil burn rates for in situ crude oil emulsion burns

Emulsion Water Content [%]	Predicted Oil Burn Rate for Emulsion Fires >3.5 m diameter [mm/min]
0	3.5
10	3.0
25	2.5
50	2.0

The processes believed to be involved with ISB of water-in-oil emulsions are illustrated in **Figure 2-4**. A two-step process is likely involved in emulsion burning:

3. Breaking an emulsion or boiling off its water to form a layer of unemulsified oil floating on top of the emulsified slick, and
4. Subsequent combustion of this oil layer.

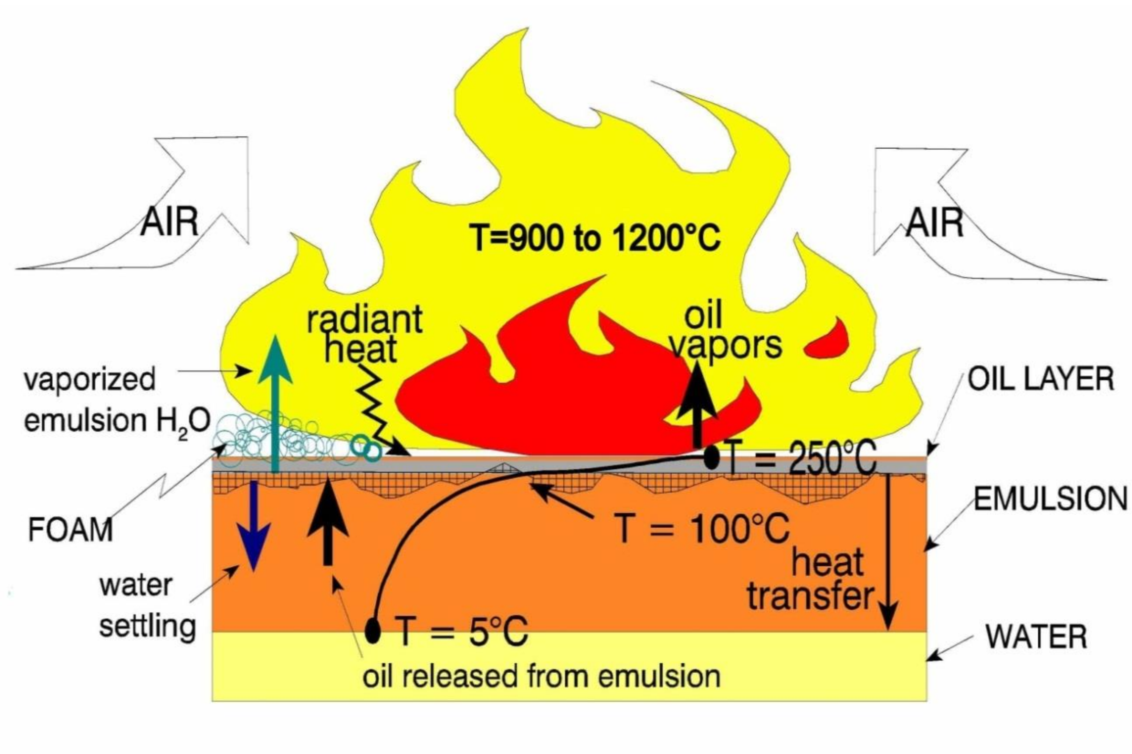

Figure 2-4 Key processes for in situ burning of emulsions (source: SL Ross Environmental Research)

High temperatures are known to break emulsions. Surface-active chemicals called emulsion breakers, common in the oil industry, may also be used.

Extinction of burning emulsions can be by the foaming action of a burning slick. Such slicks may foam over and extinguish one area of their surface, yet be re-ignited later by adjacent flames. This can result in sudden flare-ups of flame near the end of an emulsion burn. 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.

2.7 Effects of Brash and Slush Ice

Several series of experiments have addressed the effects of small ice pieces (i.e., brash ice) and slush (i.e., frazil ice) on thinner crude oil slicks typical of those that would be generated by a blowout or subsea pipeline leak. Results showed that when compared with open water, ISB in brash ice would have:

- Minimum ignitable thicknesses that are doubled, up to 2 mm.
- Flame spreading velocities that are significantly reduced.
- Burn rates in calm conditions that are approximately halved.
- The residue is about 50 to 100% greater.

The combination of the minimum ignitable thickness (3 mm for weathered oil) and residue thickness rules imply that a 3 mm slick in brash or frazil ice can be burned in situ with removal efficiencies on the order of 50% in calm conditions and 33% in wave conditions.

2.8 Air Emissions

The composition of emissions varies with the type of oil burned and the size of a burn. The vast majority of the smoke constituents are water and carbon dioxide. **Figure 2-5** (next page) shows seven components of smoke from an in situ burn and their approximate proportions.

The smoke plume emitted by a burning oil slick is the most visible aspect of ISB. Carbon particles (soot) give the smoke plume its characteristic colour. They also can obstruct visibility and hence could pose a safety hazard to operators of ships, aircraft, and motor vehicles in the immediate vicinity of a burn. The hazards from smoke can be mitigated by maintaining prescribed separation distances.

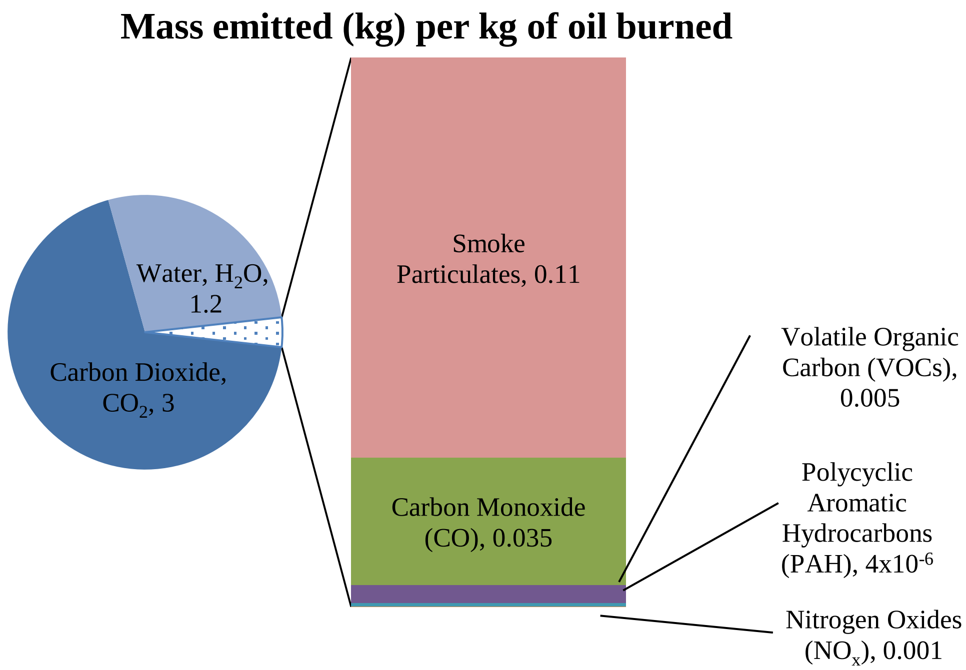

Figure 2-5 Main components of a smoke plume from an in situ burn (source: SL Ross Environmental Research)

The amount of soot per the amount of oil burned has been the subject of controversy; however, several major reviews agree on the following:

- Soot yields from dozens of burn experiments conducted in the late 1980s and 1990s, plus the oil pool fires in Kuwait, range from 2 to 20% of oil burned.
- Analysis of test burns concluded within this range found that the most important factor controlling soot yield was the fire size (diameter), although variability was high.

A recent example from monitoring in situ burn operations during the DWH spill indicated approximately 4% of oil burned on one day was emitted as smoke measured at altitude.

Particulate concentrations in a plume are greatest at the burn site and decline with increasing distance from the burn site, primarily through dilution, dispersion, fallout, and precipitation. Particulate concentrations in a smoke plume are not easy to predict because they are a function of many factors including soot yield, fire size, burn efficiency, distance downwind from the burn, terrain features, and atmospheric conditions (e.g., wind speed). Computer models have been developed to estimate the concentration of soot particles in a burn plume as a function of altitude and distance from a fire. Such models can help estimate safe separation, or set-back, distances from a fire and to decide whether or not to burn when near to populated areas.

The U.S. National Institute of Standards and Technology (NIST),[1] the National Oceanic and Atmospheric Administration's (NOAA),[2] and Environment Canada (Fingas & Punt, 2000) have each developed computer models to predict downwind smoke concentrations. The NIST and NOAA computer models are sophisticated tools that require detailed spill and meteorological inputs and should be run by experts only.

NIST has developed a simple technique for roughly estimating the maximum distance downwind over flat or complex terrain for the soot in burn plumes to dilute and disperse below a given concentration (McGrattan *et al.,* 1997). Such a downwind distance depends mainly on terrain height, atmospheric mixing depths relative to the elevation of a burn site, and wind speed. The NIST simplified tool can be used as a planning aid for estimating the maximum required separation distance for soot concentrations in smoke to dilute to below a given concentration from a proposed burn location.

2.8.1 Window-of-Opportunity for Effective Burning

As noted above, the evaporation and emulsification weathering processes have detrimental effects on the ability to ignite and effectively burn oils slicks on water and ice. As both of these processes increase in effect over time. The available time period for effective burning is often referred to as the "*window-of-opportunity*". The window-of-opportunity is generally extended for spills in ice-affected conditions compared with open water, due to decreased oil spreading and lower rates of emulsification; but, it is affected by the characteristics of the specific oil spilt.

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[1] For more information about NIST's ALOFT-FT (Walton *et al*., 1996) and ALOFT-CT (McGrattan *et al.,* 1997) computer models refer to: http://www.fire.nist.gov/aloft/aloft-ftdownload.htm and http://www.nist.gov/el/fire_protection/buildings/aloft-ft.cfm.

[2] NOAA's in situ burn calculator available from: http://response.restoration.noaa.gov/resource_catalog.php.

CHAPTER 3. SUMMARY OF RESEARCH ON IN SITU BURNING IN ICE-AFFECTED WATERS

ISB has been a primary spill response option for oil spills in ice-affected waters from the start of offshore drilling in the Canadian Beaufort Sea in the 1970s. Field experiments at that time demonstrated that on-ice burning offered the potential to remove almost all oil spilled on the surface of sea ice, with only minimal residue remaining after a burn. Since then, many studies and trials have been conducted to investigate and document the value of burning crude oil slicks in cold open water, slush ice, drift ice, pack ice, and on solid ice. There has also been considerable effort to develop technologies associated with ISB, and those applicable to ice-affected waters are summarized.

This chapter documents the key research studies on ISB in ice-affected waters over the last 40 years, according to seven broad areas of research on burning and technology development:

- Burning Oil on Solid Offshore Ice
- Burning Oil in Snow
- Burning Oil in Drift and Pack Ice Conditions
- Development of Ignition Systems
- Development of Fire-Resistant Booms
- Development of Herders for ISB

Each subsection concludes with a summary table showing key milestones in each area.

3.1 Burning Oil on Solid Offshore Ice

ISB is the response option of choice to remove oil pools on solid offshore ice. Such pools can be created by a spill directly onto the ice or indirectly by the rising of oil in spring from an earlier spill under ice that was encapsulated. There is a high degree of understanding of ignition and burning of spilled oil on melt pools.

The idea of burning oil on ice arose as a result of a groundbreaking series of experiments by the United States Coast Guard (USCG) on ice off Barrow, Alaska, USA in 1970 (Glaeser & Vance, 1971). These experiments involved several releases of 200 L of Prudhoe Bay crude oil onto a smooth multi-year floe drifting offshore in early summer. The experimental results showed, for the first time, that oil spilled on ice could be ignited simply with an oil-soaked rag and burned with high removal efficiencies (90 to 98%) without containment or promoters. In January and February 1972, a follow-up series of experiments was conducted on fast ice in the Bering Sea, also employing 200 L quantities of Prudhoe Bay crude released onto ice and snow (McMinn, 1972). Oil removal efficiencies by burning were 70% on snow and 90% on ice.

The next major step forward came as a result of a large experimental crude oil spill under fast sea ice in the Beaufort Sea at Balaena Bay, NWT, Canada in 1974/75 (Norcor, 1975). The main purpose was to investigate the fate and behaviour of 54 m^3 of fresh crude oil released under fast sea ice in the Arctic. The oil had naturally migrated upwards through the ice sheet during the spring melt and appeared in melt pools on the ice surface. A variety of cleanup techniques were evaluated:

- ISB proved by far the most effective.
- Ignition was achieved using gasoline-soaked paper towels.
- Individual burns achieved up to 90% oil removal, and one burn (**Figure 3-1**) removed 20 m^3 of oil from the surface.

- Overall about 60% of the oil originally under the ice was removed by burning. The remainder evaporated, was removed manually, or naturally dissipated by wave action after the ice sheet broke up.

Figure 3-1 Burn of oil in melt pools at Balaena Bay, NWT, Canada, 1975 (photo source: DF Dickins)

Encouraged by the success in removing oil spilled on and under ice by burning, R&D began to understand the capabilities and limitations of ISB on ice and how to ignite oil on melt pools. Belicek & Overall (1976) conducted a series of oil weathering and burning tests near Yellowknife, NWT, Canada in small metal pans designed to mimic melt pools. The tests examined minimum ignitable thickness, burn efficiency, igniters, and additives. Ignition was easily achieved by propane torch and burn efficiencies averaged 80%. Again, additives did not improve burn efficiency.

Energetex (1977) undertook a comprehensive study on the minimum ignitable thickness of crude oils on melt pools, the effects of wind on ISB of oil on melt pools, and the potential for herding agents to thicken oil on melt pools. The tests were done during winter in southern Ontario, Canada in an outdoor test facility. They found even low winds could push slicks to a downwind edge and enable ignition and burn efficiencies up to 85%. Experimental slicks could be ignited and burned in simulated winds up to 7 m/s (14 knots).

Over the winter and spring of 1979/80 a large experimental spill simulating a subsea blowout under sea ice was conducted (Dickins & Buist, 1981; Buist *et al.,* 1981). The goals of this experiment were:

- To understand what effect gas (compressed air) has on under-ice spreading and on the rate oil migrated to the surface during the spring melt period.
- To elucidate the optimum time for burning of oil contained in melt pools.
- To test, under realistic conditions, devices that could ignite oil.
- To measure how much oil was burned, how much remained as residue, and to obtain data on the chemical nature of residue.
- To obtain data on combustion products.

The experiment took place approximately eight kilometres offshore of McKinley Bay, NWT, Canada in the Beaufort Sea, under first-year fast sea ice. A total of approximately 19 m^3 of crude oil was discharged under ice from a simulated wellhead in conjunction with gas (compressed air) at three different times over the winter. The average thickness of oil on the under-ice surface was 1 mm. Of the oil discharged under the ice approximately 80% appeared on the ice surface prior to spring breakup. Fifty percent of the oil on the ice surface was burned in situ using helicopter-deployable igniters (**Figure 3-2**; next page). The oil remaining after breakup was released from the rotting ice floes as thin sheens that were dissipated by wave action.

This experiment confirmed that wind will generally blow oil on melt pools to the downwind ice edge to thicknesses of approximately 10 mm. Individual melt pool burn efficiencies were on the order of 90%. The average burn rate of small melt pool slicks was 1 mm/min.

In conjunction with the McKinley Bay, NWT, Canada field experiment, a small-scale study of burning crude oil on ice in wind conditions was undertaken at the Energetex outdoor test facility in southern Ontario and at the McKinley Bay site in December and March. A key finding of this study (Energetex, 1981) was burning oil on sea ice at air temperatures as low as -32°C (**Figure 3-3**) and in winds up to 9 m/s (18 knots).

Figure 3-2 Burning crude oil from a simulated subsea blowout under ice (photo source: Dome Petroleum)

Figure 3-3 Burning crude oil on ice at -31.5°C
(photo source: Dome Petroleum)

In the spring of 1981, an experimental spill under fast sea ice in Alaska was released to the surface by drilling into the encapsulated oil lens; the oil was burned after it rose to the surface. An estimated 95% removal efficiency was reported (Nelson & Allen, 1982).

A small field experiment was conducted in McKinley Bay, NWT, Canada to study the fate and behaviour of emulsified oil (50% water content) that was encapsulated in first-year sea ice (Buist *et al.,* 1983). The emulsions which appeared on the ice surface the next spring plus a control slick of crude oil were ignited and burned. Oil removal efficiency was 63% with the emulsion and 73% with the crude oil.

In 1991 (Bech *et al.,* 1992) and 1993 (Guénette *et al.,* 1995) researchers conducted a series of small burns of fresh, weathered, and emulsified crude on fast ice at Svalbard, Norway in 4 m^2 basins cut in the ice and filled with water (simulating melt pools). The fresh, unemulsified crude (8 mm thick) burns achieved an oil removal efficiency of 85+%. Burn efficiency decreased slightly with evaporation and decreased quickly with increasing water content over 10%. The burn rate decreased for both increasing evaporation and increasing water content. The maximum wind speed that these burns could tolerate was 10 to 11 m/s (20 to 22 knots). Gelled crude proved to be a better igniter than gelled gasoline for the emulsions (**Figure 3-4**).

Figure 3-4 Igniting emulsions on water on ice with modified igniters at Svalbard, Norway (photo source: SL Ross Environmental Research)

As part of an experimental spill at Svalbard, Norway in 2006, a crude oil slick of weathered (27% evaporated) Statfjord crude was initially 35 mm thick and 69 m^2 in size. It surfaced from under fast ice at the end of the experiment and was burned (Dickins *et al.,* 2008). More than 95% of the oil was consumed in the burn.

Table 3-1 summarizes the major milestones in R&D relating to in situ burning on solid sea ice:

Table 3-1 R&D Milestones: In situ burning on solid ice

Year	Experiment location	Key milestone
1970	Barrow, Alaska, USA	First burn on solid ice; oil easily ignited and effectively burned
1974–75	Balaena Bay, NWT, Canada	Oil released under solid ice effectively burned following spring when it surfaced
1977	Waterloo, ON, Canada	Determined minimum ignitable thickness for in situ burning and importance of wind herding of melt pool oil to achieve burnable thicknesses
1979–80	McKinley Bay, NWT Canada	Simulated a subsea blowout by discharging oil and gas; demonstrated feasibility of melt pool burning
1981–82	McKinley Bay, NWT Canada	Emulsified oil released under solid ice, effectively burned following spring when it surfaced
1991–94	Svalbard, Norway	Documented burn efficiencies for range of weathered oils; experimented with gelled gas igniter formulations

3.2 Burning Oil in Snow

During experiments with crude oil on sea ice, some of the releases were covered by drifting snow. These were ignited by the USCG. McMinn (1972) reported that the snow hindered ignition and flame spreading. The first known controlled experiments of oil ignition and burning in snow were reported by Energetex (1981):

1. Burns in small pits (100 x 50 x 10 cm) dug in an ice sheet involving pre-mixed blends of either fresh Prudhoe Bay crude or Arctic P40 diesel. The snow content of the mixtures ranged up to 55 to 83% by weight. Air temperatures were on the order of 0°C.
2. Burns in small trenches (approximately 150 x 50 x 20 cm) cut in sea ice at McKinley Bay, NWT, Canada in the winter of 1979/80 with the same two oils. Snow content ranged from 26 to 69% by weight. Air temperatures ranged from -31.5°C to 3°C (see **Figure 3-3**).

The results showed the maximum snow content (by weight) which could be ignited without a primer was 33% for diesel and 40% for fresh Prudhoe Bay crude. Burn efficiencies were 70%+. Air temperatures from -31.5 to +3°C did not appreciably affect the burns.

Nelson & Allen (1982) conducted a series of field tests to burn oil sprayed onto snow at Prudhoe Bay, Alaska. One cubic metre of fresh Prudhoe Bay crude was sprayed onto 465 m^2 of snow-covered ice for an average oil cover of 2.2 mm. The oiled snow was left undisturbed for two weeks at the first site and ignited just after application at the second. Oil penetration into the snow was initially about 1 cm. Oiled snow samples had a water content of 75 - 90%. Although some isolated oiled snow in depressions did ignite, neither the fresh nor 2-week old oiled snow could be burned efficiently as is. However, when oiled snow was ploughed into a volcano-shaped pile and ignited in the middle, heat melted the snow, allowing oil to run to the centre of the pile and feed a burn (**Figure 3-5**).

Figure 3-5 Burning oiled snow in volcano-shaped piles (photo source: Alaska Clean Seas)

Sveum *et al.,* (1991) report on a series of experiments at Svalbard, Norway on burning oil in snow; mixtures of snow and diesel or fresh Oseberg crude were used. In small-scale tests (using about 8 litres of snow), unaided ignition was possible with an oil to snow mixture of 25 and 50% snow by volume (approximately 16 and 23% snow by weight). Priming the mixture was necessary at higher snow contents. Burn efficiency was uniformly 90% or greater. Once ignited, flames would melt the snow and release oil for burning on top of melt water in the test vessel. Little difference in the results for the two oils (diesel or Oseberg crude) was noted. In field tests, a large oiled area used for oil-in-snow spreading experiments was ignited and burned using gasoline as a primer. In some experiments, oiled snow was piled into heaps and in others it was left undisturbed and ignited.

As a result of the R&D on burning oil in snow, ISB has been used operationally many times to remove smaller fuel oil spills in snow on ice by directly igniting the fuel (**Figure 3-6**). Alternatively, oiled snow can be placed in a heli-portable incinerator for burning (**Figure 3-7**).

Figure 3-6 Burning a diesel spill in snow on ice (photo source: DF Dickins)

Figure 3-7 Burning oiled snow in a portable air-curtain incinerator (photo source: Dome Petroleum)

Table 3-2 summarizes the major milestones in R&D for in situ burning oil in snow:

Table 3-2 R&D milestones: In situ burning of oil in snow

Year	Experiment location	Key milestone
1972	Bering Sea	Burned oil mixed with a range of snow contents
1979-80	Waterloo, ON and McKinley Bay, NWT, Canada	Burned crude and diesel snow mixtures at temperatures as low as -31°C to determine limits. Burn efficiencies of 70+% recorded
1982	Prudhoe Bay, Alaska, USA	Burned weathered oil deposited on snow, collecting oiled snow and burning in collection piles
1991	Svalbard, Norway	Documented conditions for burning oiled snow unaided or with combustion promoters with removal efficiencies of 90+%

3.3 Burning Oil in Drift and Pack Ice Conditions

The first recorded tests of ISB in brash ice conditions were part of demonstrations by the Alaskan oil industry in 1983 (Shell *et al*., 1983; SL Ross, 1983) that involved four test burns in a water-filled pit at East Dock in Prudhoe Bay, Alaska, USA (**Figure 3-8**; next page). For two tests, large ice blocks mined from the Beaufort Sea were grounded in the pit. Prudhoe crude oil was poured onto the water surface in the pit, allowed to drift, then ignited and burned. For the other two tests, oil was placed among floating brash ice (40 to 50% coverage of 0.3 to 1.5 m floes). In the first test with 140 L of weathered Prudhoe crude, the oil spread to 90 m^2 with an average thickness of 2.8 mm, and could not be ignited in six attempts. The second floating ice test involved 1 m^3 of fresh Prudhoe crude spread through 450 m^2 of brash ice with an average thickness of 4.6 mm. The oil was successfully ignited and burned for 7 minutes. The oil burned for an additional 23 minutes where held against the downwind edge of the pit by wind. Several subsequent ignitions of the oil against the edge of the pit were made after the main burn extinguished. In all, approximately 73% of the test oil burned.

In 1984, 1985, and 1986, burn tests were conducted at the Oil and Hazardous Material Simulated Environmental Test Tank (Ohmsett) facility, in Leonardo, New Jersey, USA inside a 46.5 m^2 wood-boomed area containing a 0.5 x 1.0 x 0.25 m tethered, 140-kg freshwater ice block (Smith & Diaz, 1987). Slightly weathered Prudhoe Bay and Hibernia crudes were used.

Figure 3-8 Burns in broken ice at East Dock, Prudhoe Bay, Alaska, 1983 (photo source: A. Allen)

- In the 1984 tests, the ice block coverage ranged from 45 to 60% where average distance between ice blocks was 20-30 cm. Oil was placed on the water between the blocks with an average thickness of 2-4 mm. Three tests were conducted in calm conditions plus one with waves. All tests ignited easily and burned efficiently, with removals of 85-95%.
- In 1985 and 1986, higher ice concentrations and emulsified oils were tested. With ice block coverage in the 75% to 80% range, fresh and evaporated unemulsified crudes had burn efficiencies of 60% to 70%. Burns of slightly emulsified crudes were much less effective (10% to 55% removal), with the lowest efficiency associated with an 18% water emulsion.

Also in 1985-86, a series of two experiments on oil burning in ice leads was conducted in an ice basin in Calgary (Brown & Goodman, 1987).

- Twenty-five burns of weathered Norman Wells crude were conducted under varying wind conditions in ice leads of various sizes and geometries cut in an ice sheet. Burn efficiencies up to 90% were possible if moderate winds pushed oil into long narrow leads. For leads of other geometries with similar winds, efficiencies were as low as 70%. Winds up to 4 m/s (8 knots) across a narrow lead had no oil herding effect and resulted in low efficiency burns. Wind-herded oil could be ignited at either the upwind or downwind edge with similar results. Evaporation of oil up to 20% did not significantly affect burn efficiency in moderate winds.
- As a small part of the same study, two tests in brash ice were conducted. The test oil was a 10% evaporated crude. Brash ice was created by breaking the ice sheet that had grown beneath the oil while it weathered in the test lead; the ice pieces were all less than 2 cm in any dimension and were thoroughly mixed into the oil prior to ignition. The presence of brash ice markedly reduced the flame spreading velocity from 0.07 m/s (0.2 ft./s) without ice to 0.03 m/s 0.1 ft./s) with brash ice; lowered the burning rate (by a factor of about 5); and somewhat lowered the range of burn efficiency (from about 85-90% down to 70-80%).

Experimental in situ burns in close pack ice conditions (9+/10ths cover), were carried out in 1986, off the coast of Nova Scotia (SL Ross & DF Dickins, 1987). Three, 1 m^3 spills of Alberta

Sweet Mixed Blend crude were released and their behaviour was monitored. One release, in drift ice (3–5 tenths) spread quickly and was not burned. The other two releases spread through and saturated the slush and brash ice over 35 and 36 m^2 areas yielding a thickness of about 30 mm between floes. Several hours after release, each was ignited using a burning, oil-soaked sorbent for removal efficiencies of 93% and 80%, respectively (**Figure 3-9**).

Figure 3-9 Burning crude oil in 9+/10ths pack ice off Cape Breton, 1986
(photo source: SL Ross Environmental Research)

In 1992, several mid-scale burn tests were conducted in a rectangular basin cut into an ice sheet on a fjord at Svalbard (Bech *et al.,* 1993). One test involved 4 m^3 of a mixture of fuel oils pumped into 9+/10ths brash ice (as a mixture of rubble pieces approximately 30 cm in size and frazil ice from blowing snow) with waves generated by a simple wave paddle (about 40 cm x 4 m) generated in the basin (**Figure 3-10**). The estimated thickness of oil was 30 mm at ignition which was accomplished with a small, gelled-crude igniter for a burn efficiency of 90%. Similar tests with 12.5 and 25% water-content emulsified oil proved extremely difficult to ignite and burn in waves. In calm conditions with sufficient primer, both ignition and burning was achieved but with lower removal efficiencies when compared with unemulsified oil. It was concluded that small ice floes and slush did not negatively affect the burning of thick oil slicks.

Figure 3-10 Burning oil in brash ice with waves at Svalbard, 1992 (photo source: SL Ross Environmental Research)

In 1993 SINTEF carried out a large field experiment in pack ice in the Barents Sea. One part of the experiment involved attempting to ignite seven-day weathered crude oil slicks in a 70% ice cover (Singsaas *et al.,* 1994). The oil proved to be too weathered and thin for ignition.

- In 1994, another series of experiments on burning crude oil and emulsions in brash ice was conducted in a 15 m diameter, circular basin that had been cut in ice of a fjord at Svalbard (Guénette & Wighus, 1996; Guénette & Sveum, 1994). Fresh, weathered, and emulsified Statfjord crude oils were used. The basin contained slush ice from blowing snow and ice pieces from 0.5 to 3 m in diameter.
- In a pre-test burn, 200 L of fresh crude was easily ignited and burned in the compacted brash ice. Oil initially spread to cover 9 m^2, equivalent to a thickness of 22 mm. At the end of the burn (14 minutes) it had spread to 15 m^2. No removal efficiency was reported for this burn.
- In a full-scale test, 8 m^3 of fresh crude was placed in 20% ice cover (most of the ice and slush was submerged by the thick oil), which resulted in an initial thickness of 56 mm. This slick was easily ignited with a simple gasoline-soaked sorbent and yielded a 99% removal efficiency. The next test involved 6 m^3 of a 50% water-in-18%-evaporated-crude emulsion in 50% ice cover. This emulsion proved very difficult to ignite, eventually requiring 4 m^3 of fresh crude oil as primer to achieve 75% removal efficiency.
- Their final test involved 2.7 m^3 (30 mm estimated thickness) of 20% water-in-crude emulsion in a 50% ice cover; this was successfully ignited using a gelled gas igniter containing emulsion breaking chemicals. Gasoline was also used as primer. A removal efficiency of 95% was achieved with prevailing winds of 8 to 11 m/s (16 to 22 knot) pushing the burning oil and ice against the downwind ice edge.

In 2002-03, a series of experiments was undertaken to investigate minimum ignitable thickness, combustion rate, residue amount, and the effects of waves when burning thin oil slicks in two ice conditions: 1) frazil or slush ice typical of freeze-up, and 2) brash ice typical of break-up (SL Ross *et al.,* 2003). The focus was on thin oil slicks which could be generated by a blowout or a subsea oil pipeline leak. The project consisted of small-scale burns in a chilled wave tank in

Ottawa and mid-scale burns in an outdoor wave tank at Prudhoe Bay, Alaska, USA (**Figure 3-11**).

Figure 3-11 Test burns in brash ice with waves in Prudhoe Bay, Alaska, 2003 (photo source: SL Ross Environmental Research)

The small-scale experiments consisted of:

- Minimum ignitable thickness tests for three degrees of weathered oil for four Alaskan crudes as tested on open water, brash (represented by ice cubes) and frazil ice, or slush ice (represented by pulverized ice cubes), and,
- Burn rate and removal efficiency tests in calm and low wave conditions with 3 mm thick slicks spread on top of ice for the three weathering and ice conditions above.

Mid-scale tests mimicked the small-scale design for open water, brash ice (grown in a nearby pit from Prudhoe Bay water), and a layer of frazil ice (simulated by using snow in water). In general, some rules-of-thumb derived from the small- and mid-scale experiments were:

- Minimum ignitable thickness of -
    - fresh crude in frazil ice or small brash ice is up to double that for open water, about 1-2 mm.
    - evaporated crude oil in frazil ice or small brash ice pieces can be higher than on open water, but, is within the range for weathered crude on water, about 3 mm with gelled gasoline igniters.
- For a given spill diameter, the burn rate in calm conditions is nearly 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.
- Residue remaining on broken ice in calm conditions is about 50% greater than on open water or 1.5 mm. Residue remaining in brash or frazil ice in waves is slightly greater than in calm conditions, at about 2 mm.

The combination of the minimum ignitable thickness of 3 mm for weathered oil, and the residue thickness rules-of-thumb imply that 3 mm slicks in brash or frazil ice can be burned in situ with removal efficiencies on the order of 50% in calm conditions and 33% in wave conditions.

SINTEF ran a large multi-year experimental programme to quantify the ignitability and burnability of weathered crude oils in pack ice conditions (Brandvik *et al.,* 2010b). The experiments involved lab-, mid- and field-scale experiments in which five crude oils were tested in open water, 50% brash ice, and 90% brash ice. The ignitability and burnability over time of the weathered oils were measured in a laboratory apparatus. In addition, the weathered oils (250 to 400 L, depending on water content) from the field tests were burned in their entirety in a flume cut in fast ice (**Figure 3-12**; next page). The study concluded that:

- All test oils eventually became unignitable due to the combination of evaporation and emulsification,
- When weathered in ice, oils remained ignitable longer than in open water due to slower evaporation and emulsification, and
- Increasing ice cover lengthened the window-of-opportunity for burning.

Figure 3-12 Burning oil weathered in brash ice in meso-scale burn pit at Svalbard, Norway, 2007 (photo source: SINTEF)

As a part of a larger Oil in Ice Joint Industry Programme (JIP) experimental spills were conducted in close pack ice (7 to 9 tenths) in the Barents Sea (Brandvik *et al.,* 2010c; Fritt-Rasmussen & Brandvik, 2011; http://www.sintef.no/Projectweb/JIP-Oil-In-Ice/Publications/):

- One consisted of 2 m^3 of crude left to weather for 12 hours in pack ice before being ignited with plastic baggies of gelled gasoline. A vigorous burn ensued (**Figure 3-13**; next page) that consumed approximately 95% of the oil.
- Another spill of 7 m^3 of fresh crude weathered for five days in pack ice ranging in concentration from 7 to 9 tenths. Samples of the oil were ignitable for four days, but not ignitable on the fifth day.

Results confirmed that spills in pack ice conditions have an extended window-of-opportunity for ISB due to slower weathering of the oil in pack ice when compared with open-water conditions.

Table 3-3 (second page) summarizes the major milestones relating to ISB of oil in drift and pack ice conditions.

Figure 3-13 Burning 2 m^3 experimental spill in pack ice on the Barents Sea, 2009 (photo source: SINTEF)

3.4 Development of Ignition Systems

Many different ignition devices have been used to attempt to ignite oil spills.

In 1967, four attempts were made to ignite seemingly thick oil slicks near the *Torrey Canyon* vessel using pyrotechnic devices containing sodium chlorate, but were unsuccessful (Swift *et al.,* 1968; Anonymous, 1967). It was concluded that the spilled oil was too emulsified to ignite. Oil on shore from the *Torrey Canyon* spill also proved virtually impossible to ignite and burn. While some success was reported using flame throwers to ignite unemulsified oil in pools between rocks (Swift *et al.,* 1968), emulsified oil could not be burned on the beach unless flame was applied directly to the oil. Once the igniter flame was removed, combustion stopped.

Starting in 1977, considerable effort was devoted to developing an aerial ignition capability in support of potential spills from offshore exploration activities in the Beaufort Sea. Energetex Engineering (1978) evaluated and tested Kontax, Kontax with gasoline, solid propellant, solid fuel, and gasoline with sodium. Solid-fuel and solid-propellant igniters with a fuse wire were ranked highest. Subsequently, two igniters were developed in Canada: the Dome igniter (Buist *et al.,* 1981; Energetex, 1982a, 1982b), and the EPS igniter (Meikle, 1981a, 1981b; Twardawa & Couture, 1983). Only the Dome igniter was sold commercially; several thousand remain in the Alaska Clean Seas inventory.

Table 3-3 R&D milestones: In situ burning of oil in drift and pack ice conditions

Year	Experiment location	Key milestone
1983	Prudhoe Bay, Alaska, USA	First experiment using in situ burning to effectively burn oil in broken ice conditions
1984-86	Ohmsett Facility, New Jersey, USA	Effective burning of crude oil between ice blocks and effect of emulsification on burning
1985-86	Calgary, Alberta, Canada	Effective burning of wind-herded oil in leads
1986	Cape Breton, Nova Scotia, Canada	Documentation of spreading rates in various ice concentrations; effective use of in situ burning in dense ice conditions
1992	Svalbard, Norway	Effective use of in situ burning in dense brash and frazil ice
1993	Barents Sea	Identification of limits on ignition of oil in pack ice
1994	Svalbard, Norway	Effective burning of oil in low and modest ice concentrations and of emulsions using combustion promoters
2002-03	Prudhoe Bay, Alaska, USA	Documented variations in burn parameters for thin slicks in brash, frazil, and slush ice
2007-10	Trondheim and Svalbard, Norway	Documented variation in ignitability and burning efficiency for range of weathering and emulsification conditions; established parameters for windows-of-opportunity in ice conditions
2009	Barents Sea	Field verification of 2007 experiments

Laser-based ignition systems received considerable attention in the 1970s and 80s (Waterworth, 1987; Whittaker, 1987; Frish *et al.,* 1989; Laisk, 1976). A land-based system proved capable of igniting oil slicks on water (Frish *et al.,* 1989). The various components of a helicopter-borne system were researched; however, the system was never commercially developed (Frish *et al.,* 1986, 1989).

In the mid-1980s in Alaska, a forest fire fighting tool known as the Heli-torch was identified as a likely, effective aerial ignition option for oil spills (Allen, 1986). Considerable testing and refinement of the device (Allen, 1987) has resulted in the Heli-torch being stockpiled as the igniter-of-choice for ISB from an aerial platform, supplanting the Dome igniter.

Research was conducted in the mid-1990s that focused on extending the capabilities of ignition systems for water-in-oil emulsions with up to 40% water content (S.L. Ross, 1989; Bech *et al.,* 1992; SINTEF & S.L. Ross, 1993). In related projects, emulsions could be burned. However, higher-strength igniters using gelled crude oil, rather than the conventional use of gelled gasoline, were required for successful ignition. Guénette and Sveum (1995) used gelled fuels (gasoline, diesel, and crude), an emulsion breaker, and an anti-foaming agent to ignite and burn emulsions with water contents up to 50%. The results showed potential for the concept of a one-step, break-and-burn process for emulsions. During trials off Lowestoft, England in 1996 (Guénette & Thornborough, 1997), the concept was demonstrated using a Heli-torch to deliver an emulsion breaker and fuel mixture to successfully ignite and burn an emulsion containing 25% water.

There has been little work done on aerial ignition system development for ISB in the last two decades. The Heli-torch had been used in the NOBE experiment in 1993 (Fingas *et al.,* 1994), the Lowestoft trials in 1996 (Thornborough, 1997), and two inland burns in Utah (Williams *et al.,* 2003). Other field trials and operational uses of ISB have used simple, ad-hoc igniters. For example, during the response to the DWH blowout in 2010, igniters were assembled from off-the-shelf components: a marine signal flare, a plastic bottle, and gelled fuel (Mabile, 2010).

The U.S. Navy Supervisor of Salvage undertook development of an igniter that did not require a helicopter for deployment and could be shipped safely by surface or air (Moffatt & Hankins, 1997). Through an iterative process involving experimentation with different fuel compounds, a flare-type device was produced yet never commercialized, which could successfully ignite and burn diesel fuel and 25% water content emulsions.

Use of a sodium-silicon compound as an igniter was examined by Buist (2005). Granules of sodium silicide (NaSi) were able to ignite slicks of fresh crude oil thicker than 1 mm; but, they extinguished before the oil and NaSi was completely consumed. Although the granules could ignite fresh crude, the short duration of flames (about 10 seconds) compared with several minutes for more conventional ignition systems (2 minutes to 10 minutes), raised questions about the ability of NaSi granules to ignite weathered oil slicks which need to be pre-heated before ignition will occur. Also, the granules remaining after extinction could pose safety concerns for residue recovery operations.

Ignition of spilled oil from a fixed-wing aircraft has advantages over hand-held igniters and the use of a Heli-torch under rotary wing aircraft for certain spill circumstances. Primary among them are: the ability to carry much larger payloads approaching 1,000 gallons of gelled fuel, and to deliver payloads tens to hundreds of miles from a staging area.

A series of "*proof-of-concept*" ground tests were conducted in 2010 and 2011 to determine whether gelled fuel could be ignited and achieve a sustained burn at simulated release speeds of 80 to 100 knots, corresponding to the speed of a small fixed-wing aircraft (Preli *et al.,* 2011). The tests were conducted at the Beacon Training Center in Kenai, Alaska:

- Numerous tests were conducted with a variety of nozzle/shroud configurations at temperatures between 7°C to well below freezing.
- A trailer-mounted wind machine simulated the winds during the release of various mixes of gelled fuel (gasoline, diesel, and aviation gas).
- The nozzle/shroud configurations tested a variety of orientations downwind to reduce the relative velocity of burning gelled fuel globules within the wind-induced air.

The results demonstrated the possibility of igniting gelled fuel at simulated fixed-wing aircraft speeds approaching 110 knots.

Table 3-4 summarizes the major milestones in R&D relating to the development of ignition systems for in-situ burning.

Table 3-4 R&D milestones: Development of ignition systems

Year	Experiment location	Key milestone
1967–77	Various spills	Attempts at in situ burning using ad-hoc igniters, some with wicking agents, with mixed results
1977–80	Various laboratories and field experiments in Canada	First concerted attempt to develop aerial ignition capability; evaluation of various methods; production of two prototypes
1970s–80s	Various	Development and testing of laser-based ignition system, not commercially developed
1986	Alaska, USA.	Fire fighting ignition system, Heli-torch, evaluated and developed for use in in situ burning
1992–93	Canada and Norway	Development of better Heli-torch fuels for igniting emulsions
2010	U.S. Gulf of Mexico	Extensive use of simple site-built igniters used in *Deepwater Horizon* response
2011	Alaska, USA.	Initial testing of concept for ignition system deployed by fixed-wing aircraft

3.5 Development of Fire-Resistant Booms

Removal efficiency increases with increased initial slick thickness. In order to thicken and contain oil spills on water for ISB, a variety of fire-resistant booms have been developed over the years. Allen (1999) provides a good summary of advances in boom technology at that time, including a comparison of refractory fabric booms, stainless steel booms, and actively-water cooled booms.

Efforts in North America to develop fire-resistant booms began in 1976 with work on water-spray and air-bubble barriers for containing burning oil from subsea blowouts (Purves, 1978; Comfort *et al.,* 1979; Purves & Daoust, 1978). The barriers were found to be impractical because of the poor containment efficiency of air-bubbles and the operational complexity of water-spray designs. For the same application, work on development and testing of a "*quickie*" boom to be rapidly constructed using empty steel oil drums and fire blanket was undertaken (McAllister, 1979). The device was tested in a small pond and proved reasonably effective at containing oil burning on water. The “*quickie*” design was supplanted by more effective metallic fire boom designs within two years.

In 1979, three large spills catalysed efforts to develop fire-resistant containment boom: the IXTOC-1 blowout, the *Burmah Agate* spill, and the sinking of the *Atlantic Empress*.

- The IXTOC-1 offshore blowout revealed the difficulties associated with large quantities of oil being continuously released over a long time period (Ross *et al.,* 1979). This very large spill (500,000 m^3 in total) highlighted the potential for ISB in responding to fixed-point spills.

- The *Burmah Agate* spill, which released 250,000 bbls of oil into the GOM in November, 1979, illustrated the potential for ISB to remove large amounts of surface oil (186,000 bbls burned for a 74% removal). Performance of existing booms highlighted the need for fire-resistant ones to contain burning oil (Kana *et al.,* 1981).
- The *Atlantic Empress*, a 288,000 dead weight tonnage tanker, suffered a vessel casualty with a fire that consumed all of the oil on board and the vessel sinking, dramatically illustrated the potential for ISB to remove oil from a sea surface (Horn & Neal, 1981).

From 1979 to 1981, Dome Petroleum Ltd., the main explorer for offshore oil in the Canadian Beaufort Sea, developed a heavy-duty stainless steel, fire-resistant boom for long term offshore use (Buist *et al.,* 1983b). Their test programme involved field testing prototypes at the Ohmsett facility in New Jersey, in British Columbia, and Nova Scotia. A 77 m length of the final design was constructed and stockpiled in the Canadian Beaufort Sea for operational use.

In the early 1980s, efforts were underway in Alaska to develop lighter, fire-resistant boom for short-term use (Industry Task Group, 1983; Allen, 1986a), and in Canada to develop lighter, lower-cost boom designs (Meikle, 1983). The Alaskan work resulted in the 3M Fire Boom. Various iterations of improved 3M boom designs (now produced by Elastec/American Marine – see below) have been stockpiled around the world. In July 1988, a field test of 3M Fire Boom was carried out in a fjord at Svalbard, Norway. The trials involved 90 m of boom and 1,900 L of Statfjord crude. Unweathered oil in the pocket of the boom was ignited with a Heli-torch and burned for approximately 30 minutes (Allen, 1992).

In 1989, a test burn was conducted very early in the response to the *Exxon Valdez* oil spill. During the evening of the second day an estimated 57 to 114 m^3 of slightly emulsified (20 to 30% water) North Slope crude was burned using 136 m of 3M Fire Boom (Allen, 1991a). The test burn was ignited using a floating bag of gelled gasoline. The burn lasted 75 minutes, of which 45 minutes involved intense burning and flames reaching 60 to 90 m into the air. This was the first recorded use of manufactured, fire-resistant boom at a major spill incident. Residue remaining in the boom was about 1.1 m^3 of stiff, taffy-like material (Allen, 1991b). By the time additional burns were attempted, a storm had further emulsified the slick rendering it unignitable (Exxon, 1990).

On August 12, 1993 two experimental burns were conducted offshore St. John's, Newfoundland that involved 3M Fire Boom. The boom survived the first 1.5 hours in 50 cm waves with 8 to 11 km/h (16 to 22 knot) winds. Despite some signs of fatigue and self-abrasion, it was considered acceptable for another burn. Seventy-five minutes into a second burn, several flotation units were lost from one section and containment began to fail. The test was stopped and the boom re-examined. Preliminary on-site results indicated self-abrasion of the fire-resistant fabric had occurred (Raloff, 1993; NOBE Newsletter, 1993; OSIR, 19 August 1993). Although the main objective of this landmark field experiment was to document emissions from an in situ burn, there were useful observations of boom performance (Fingas *et al.,* 1994).

- Oil was contained in commercially-available, fire-resistant boom and ignited using a Heli-torch.
- After the first burn of 48 m^3 of crude oil over 90 minutes, some fatigue was noted in the stainless steel core and some portions of the fire-resistant fabric were missing. The boom was judged to be fit for a second burn.

- After the second burn of 29 m^3 of crude oil over 80 minutes, a prototype section inserted in the boom for testing purposes was missing its float logs.
- Subsequent inspection showed improper construction of the prototype section. The boom was judged to be in good overall condition but the apex could not be used for another burn.

The USCG Research and Development Center and the U.S. Department of Interior's Minerals Management Service[3] (MMS), jointly sponsored a series of oil containment tests of fire-resistant booms using the Ohmsett facility (Bitting & Coyne, 1997). The tests were performed using the standard Ohmsett test procedure for containment boom testing, which was subsequently adopted by ASTM as *F2084 - Standard Guide for Collecting Containment Boom Performance Data in Controlled Environments* (ASTM, 2012). Bitting and Coyne (1997) suggested that increased a buoyancy-to-weight ratio would be beneficial for performance, but the tests showed the generally low B:W ratios of fire-resistant booms, in the range of 2.0 to 3.5, were adequate.

Tests were performed at the USCG Fire and Safety Test Detachment in Mobile, AL to evaluate the use of propane for testing fire-resistant boom (Walton *et al.,* 1997). Propane has an advantage over pooled, liquid hydrocarbons because it produces a relatively smoke-free burn which simplified permitting for testing. Heat fluxes measured from a propane fire were approximately 60% of that from a liquid fuel fire.

Using the same fire-resistant boom from the NOBE trials, mid-scale and full-scale tank tests were performed to measure the effects of waves and water current combined with heat flux (McCourt *et al.,* 1997). Alternating one-hour periods of heat exposure followed by waves were used to simulate the collection and burning phases of an in situ burn. Observed boom degradation was similar to that measured in the NOBE experiment, but at a slower rate. This was concluded to be the result of the lower heat flux produced by the propane used to provide heat exposure for the tests. A system of injecting compressed air into propane flames was devised that increased the heat flux from the propane flames to equal that of an in situ burn of liquid petroleum (McCourt *et al.,* 1999).

As in the earlier tests, an unused section of boom from the NOBE trials was subjected to alternating one-hour periods of flames and waves. The measured temperatures and heat flux were comparable to a crude oil fire, and the observed degradation of the boom was similar to the NOBE experiment. It was concluded the test protocol would be a reasonable analogue for screening fire-resistant booms. An enhanced propane fire boom test system was purchased for the Ohmsett facility and used to test several fire boom and fire blanket designs.

Further development of a standardized test protocol was done in a purpose-built wave tank using diesel fuel (Walton *et al.,* 1998; Walton *et al.*, 1999). A 15 m section of boom was positioned in a circle within the tank and subjected to alternating one-hour periods of waves and burning oil. Five different booms were tested; as the objective was to evaluate the test protocol, they were identified only generically. The test protocol was judged to be the most realistic simulation to date of the thermal and mechanical stresses on a fire-resistant boom. The protocol was developed in conjunction with the ASTM subcommittee on ISB, and led to a standardized test method*, F2152-07 Standard Guide for In Situ Burning of Spilled Oil: Fire-Resistant Boom* (ASTM, 2012). The standard allows for either diesel fuel or enhanced propane testing.

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[3] MMS has since been divided into the Bureau of Ocean Energy Management (BOEM), the Bureau of Safety and Environmental Enforcement (BSEE), and the Office of Natural Resources Revenue (ONRR).

The Dome stainless steel boom was originally designed and built in the 1980s with somewhat rigorous design criteria related to its intended use in the Arctic. Consequently, it was originally heavy, expensive, and difficult to deploy. It was re-engineered in the late 1990s to reduce its size, weight, cost, and handling difficulties (Buist *et al.,* 1999). The re-engineered prototype was subjected to the draft ASTM burn test protocol (then under development) using both diesel and the Ohmsett facility's enhanced propane system. This boom was also evaluated using standard oil containment testing at Ohmsett where components were tested in the laboratory to confirm long-term performance. Results suggested the re-engineered Dome boom could be either used as a stand-alone, fire-containment boom or a high-strength, durable burn pocket between two lengths of conventional fabric fire boom.

In 1999 and 2000, the USCG conducted three on-water exercises to develop and practice procedures for ISB operations (Bitting *et al.,* 2001). Elastec water-cooled fire boom was used and oranges were released as a substitute for oil. Several modes of operation were examined including direct containment of the "*oil*" for burning, as well as the use of conventional boom to collect and concentrate oil prior to it being funnelled into the fire boom for burning. The results were used to refine operational procedures for the use of ISB as a viable response tool.

In the late 1990s and early 2000s, a series of fire boom tests were conducted at the Ohmsett facility using the propane fire test system in concert with the draft (at that time) ASTM test protocol.[4] A total of 11 fire-resistant booms and fire-resistant protective blankets were tested and provided the basis for acceptance of several designs as likely candidates for use in the field[5].

As part of a multi-year laboratory and field experiment to examine oil spill behaviour in ice and various response options, tests were performed with fire-resistant boom in a range of drift ice concentrations (Potter & Buist, 2010).

- In 2008, tests were performed without oil and confirmed the ability of two commercially-available fire booms to contain ice while under tow, such that a "*contain-and-burn*" operation could be performed in light ice conditions. Two specific booms were tested: 1) the Elastec/American Marine Boom (formerly known as the 3M Boom), and 2) the AFTI PyroBoom. Each was able to contain ice at towing speeds in excess of normal containment limits of oil, i.e., 0.35 to 0.5 m/s (0.7 to 1 knot). Tow loads were measured and found to be about twice the loads experienced in open water.
- In 2009, the same two booms were tested in two different ice conditions: in 3/10 to 5/10ths ice (**Figure 3-14**; next page), and in trace ice conditions (**Figure 3-15**; next page). Each boom was manoeuvred to capture ice sufficient to fill the boom's apex. Some 4 m^3 of fresh crude was released into contained ice and then ignited. A high percentage of the oil was removed, some 98% in the first test and 89% in the second, showing the ability of fire-resistant booms in light drift ice.

[4] Refer to http://www.bsee.gov/Research-and-Training/Technology-Assessment-and-Research/tarproject categories/In-Situ-Burn-Research.aspx for more information.

[5] The results of the Ohmsett and Mobile, AL testing and the resulting ASTM standard for fire-boom testing, were generally corroborated during the *Deepwater Horizon* response in that booms that performed well in testing did well in the response effort, and vice versa.

Figure 3-14 Test with 3 to 5/10th small floes (photo source: SL Ross Environmental Research)

Figure 3-15 Test with brash and slush ice (photo source: SL Ross Environmental Research)

Table 3-5 summarizes the major milestones in R&D relating to the development of fire-resistant boom for in-situ burning:

Table3-5 R&D milestones: Development of fire-resistant booms

Year	Experiment location	Key milestone
1970s	Vancouver and Ottawa, Canada	Initial attempts to develop fire-resistant boom, including air-bubble and water-spray barriers
1983	Vancouver, Canada	Development of stainless steel fire-resistant boom for offshore use
1988	Alaska, United States	Development of 3M fabric-based fire-resistant boom
1989	Alaska, United States	Successful use of 3M fire-resistant boom in *Exxon Valdez* response
1997–99	Canada/United States	Development of standard testing protocol for fire booms
1999	Canada/United States	Re-engineering of stainless steel fire-resistant boom to reduce weight and cost
1990s–2000s	Illinois, United States	Development of water-cooled fire-resistant boom
2008–09	Barents Sea	Testing of two fire-resistant booms in drift ice, including capture and towing of ice floes and subsequent burning of oil

3.6 Development of Herders for In Situ Burning

The use of surface-active chemicals (surfactants), sometimes called oil herders or surface collecting agents, to contract and contain oil slicks on the surface of water is well understood (Garrett & Barger, 1972; Rijkwaterstaat, 1974; Energetex, 1981; Pope *et al.,* 1985; Walker *et al.*, 1993). Such products have the ability to spread rapidly over a water surface into a monomolecular layer as a result of their high spreading coefficients or spreading pressures.

- The best herding agents have spreading pressures in the mid-40 mN/m range[6], whereas most crude oils have spreading pressures in the 10 to 20 mN/m range. Consequently, small quantities (applied at about 15 L per linear kilometre of slick edge; approximately 6 gal/mile) can quickly displace thin films of oil from much larger areas of water surface, effectively shrinking spilled oil into thicker slicks.
- Herders sprayed onto water surrounding an oil slick work by reducing the surface tension of surrounding water considerably (from about 70 mN/m to 20–30 mN/m). When the surfactant's monomolecular layer reaches the edge of a thin oil slick, it increases the interfacial forces acting on that slick edge and the oil contracts into thicker layers.

Herders do not require a boundary to "*push against*" even in unbounded open water. A conceptual drawing of the herding process is shown in **Figure 3-16**. Although commercially manufactured in the 1970s, herders were not used offshore because they only worked in very

[6] mN/m means milli-Newtons per meter and is numerically equivalent to a dyne per cm.

calm conditions, containment boom was still needed to hold or divert slicks in wind speeds above 2 m/s (4 knots), and breaking waves disrupted a herder's monomolecular layer.

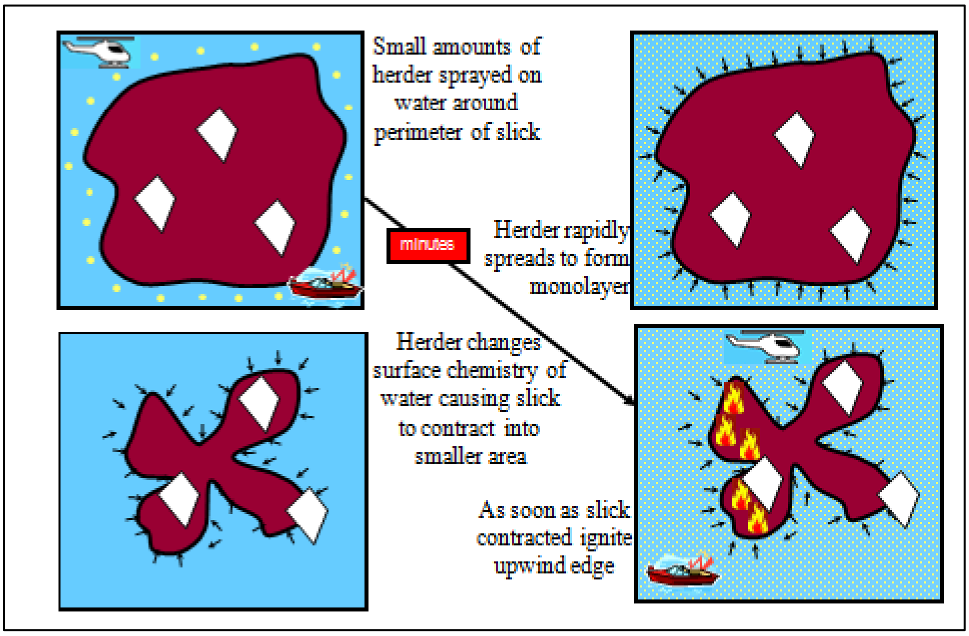

Figure 3-16 Concept for use of herders to contract oil slicks in drift ice for ignition and burning (source: SL Ross Environmental Research)

A research programme began in 2003 to advance oil spill response in ice and found herding agents persisted long enough to enable ISB of relatively fresh, fluid oils in broken or drift ice. This multi-year, multi-partner series of studies (Buist *et al.,* 2011) included:

- A very small scale (1 m^2) preliminary assessment in 2003 of a shoreline-cleaning agent with herding properties to assess its ability to herd oils on cold water and among ice (SL Ross, 2004).
- Small-scale (1 m^2) experiments in 2005 explored the relative effectiveness of three hydrocarbon-based herding agents in simulated ice conditions. This was followed by larger-scale (10 m^2) quiescent pan experiments to explore scaling effects and small-scale (2 to 6 m^2) wind/wave tank tests to explore their effects on herding efficiency. Finally, some small ignition and burn tests were conducted and identified ThickSlick 6535 as an effective herding agent on cold water and in ice conditions (SL Ross, 2005). These initial experiments provided the impetus for further, larger scale studies.

More experiments were done with the ThickSlick 6535 herder at a scale of:

1. 100 m^2 in the indoor, Ice Engineering Research Facility Test Basin of the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire, USA in November 2005 to explore the effects of brash ice concentration and waves on herder efficacy, and
2. 1,000 m^2 at the Ohmsett facility in artificial pack ice in February 2006 to explore the effects of drifting ice and swell waves on the herding action.

Also a series of 20 burn experiments (**Figure 3-17**) was performed in 2006 with ThickSlick 6535 at a scale of 30 m^2 in a specially-prepared test basin containing brash ice in November 2006 at the Fire Training Grounds in Prudhoe Bay, Alaska, USA with fresh crude oil (SL Ross, 2007). Fresh and evaporated crude oil slicks were successfully herded, ignited, and burned in situ in ice concentrations up to 30% at temperatures as low as -17°C. Removal efficiencies measured for the herded slicks were comparable to those achievable for equivalent-sized slicks on open water contained by a boom.

Figure 3-17 Burn test with ThickSlick 6535 at Prudhoe Bay, Alaska in 2006 (photo source: SL Ross Environmental Research)

Field tests in Barents Sea pack ice were conducted in 2008. One test released 630 L of fresh Heidrun crude in a large ice lead, where free-drifting oil was allowed to spread for 15 minutes until it was too thin to ignite (0.4 mm). Then, ThickSlick 6535 herder was applied around the slick periphery. The slick contracted and thickened for approximately 10 minutes, at which time the upwind end was ignited using a gelled gasoline igniter. A 9-minute long burn ensued that consumed an estimated 90% of the oil (Buist *et al.,* 2010b; **Figure 3-18**).

Figure 3-18 Burn of herded slick in pack ice lead (*Left*: near start; *Right*: near end) (photo source: SL Ross Environmental Research)

A series of laboratory and test tank studies to identify better herding surfactants was completed between 2008 and 2010. The studies involved 1 m^2 and 10 m^2 herding tests with ice in the laboratory, and 17 m^2 herding tests with ice at CRREL, Hanover, New Hampshire (**Figure 3-19**). It was during this period that the OP-40, silicone-based, herder was identified as being more efficient at herding than ThickSlick 6535 (Buist *et al.,* 2010b).

Figure 3-19 Testing of silicone-based herding agents at the CRREL facility (*Left*: oil release; *Centre*: oil spread to equilibrium; and *Right:* contraction to new equilibrium after herder addition to water) (photo source: SL Ross)

Based on positive experimental findings for herder effectiveness, work on techniques for applying herding agents to slicks in ice-affected water began in 2010 (Buist & Belore, 2011). Laboratory studies of nozzle spray patterns and potential spray systems provided basic design data for aerial and boat-based application systems. A helicopter-borne application system for Arctic use is being developed and will be tested in the near future (Lane *et al.,* 2012).

The 2010 Ohmsett experiments on the use of herders as a rapid-response technique for use in open water showed that herders on open water:

- Restrain a slick for more than 45 minutes in calm waters,
- Restrain a slick in a non-breaking swell condition, but the constant stretching and contracting of the herded slick elongates and slowly breaks it into smaller segments.

Breaking or cresting waves rapidly disrupts the herder's monomolecular layer and the oil slick resulting in many small slicks (SL Ross, 2012).

Two herding agents (ThickSlick 6535 and SilTech OP-40) have been placed on the U.S. EPA National Oil and Hazardous Substances Pollution Contingency Plan (NCP) Product Schedule[7] for consideration for use in U.S. waters and were commercially available as of June, 2012. Samples of these herders have also been submitted to Environment Canada for consideration for use in Canadian waters.

Table 3-6 summarizes the major milestones in R&D relating to the development of herding agents for in-situ burning.

[7] Refer to http://www.epa.gov/oem/content/ncp/index.htm#schedule for more information.

Table 3-6 R&D milestones: Development of herders for in situ burning

Year	Experiment location	Key milestone
2003	Ottawa, Canada	Initial feasibility tests with herders in cold water and ice
2005	Ottawa, Canada	Lab- and mid-scale tests to evaluate different herder formulations and examine wind/wave effects
2006–07	CRREL facility, New Hampshire; Ohmsett facility, New Jersey; and Prudhoe Bay, Alaska, USA	Large-scale tests and test burns with herding agents
2008	Svalbard, Norway	Successful field test and burn of 630 L experimental spill
2008–10	Ottawa, Canada; and CRREL facility, New Hampshire, USA	Further development and testing of more effective herder formulations
2012	Canada/United States	Development of a helicopter-borne application system

3.7 Summary of ISB Knowledge in Ice

Table 3-7 (next page) summarizes the present knowledge of in situ burning in ice-affected waters with a variety of oil types. Five categories of ISB knowledge are denoted in the table, tabulated by the range of possible ice conditions:

- Documentation of the fate and behaviour of a spill of the various oil types from the perspective of ISB feasibility and timing,
- Determining the feasibility of igniting various oils,
- Determining the effectiveness of fire-resistant boom designs,
- Determining the effectiveness of herding agents, and
- Characterising and quantifying residue.

Table 3-7 Summary of experiments and operational experience with in situ burning on different oil types in various sea ice conditions

ISB TOPIC	Degree of Ice Coverage and Ice Type								
	Ice Free and Open Water ***<1/10***	**Very Open Drift Ice** ***1/10 to 3/10***	**Open Drift Ice** ***4/10 to 6/10***	**Close Pack Ice** ***7/10 to 8/10***	**Very Close Pack Ice** ***9/10 to <10/10***	**Fast Ice**	**Leads**	**Brash and Frazil/Slush Ice**	**Multi-year Ice**
Spill behaviour for ISB	FC, WC, EC, DF, RF	FC, WC, DF	FC	FC, WC, EC, DF, RF	FC, WC, EC, DF, RF	FC, WC, EC, DF	FC	FC, WC, EC, DF	One semi-successful field expt. with FC
Ignition	FC, WC, EC, DF, RF	FC		FC, WC, DF, RF	FC	FC, WC, EC, DF	FC, WC, EC	FC, WC, EC	
Fire boom	FC, WC, EC, DF	FC							
Herders	FC, WC	FC,WC				FC	FC	FC	
Residue	FC, WC, EC, DF	FC			FC	FC, WC, EC, DF	FC, WC	FC, WC, EC	

NA = Not Applicable
FC = fresh crude
WC = evaporated crude
EC = emulsified crude
DF = distillate fuel oil
RF = residual fuel oil

To summarize the table:

- In terms of spill behaviour as it applies to ISB, there have been numerous studies in a wide range of ice conditions with a variety of oil types.
- There have also been a large number of experiments on ignition of fresh, evaporated, and emulsified crude oils spilled in a variety of ice conditions.
- Fire booms have been tested extensively in open water and to some extent in very open drift ice conditions. Fire boom use in higher ice concentrations is not considered feasible, based on those tests.
- Herders have been tested primarily with fresh crudes and moderately evaporated crudes in very open drift ice conditions and to a lesser extent in open water. Some experiments have been carried out with fresh crude on melt pools, in leads, and in brash and frazil ice conditions.

Experiments that involved measuring the residue remaining and/or physical and chemical characteristics from a range of oil types have primarily involved open water conditions. Experiments involving residue have also been conducted in very open drift ice and close pack ice. Experiments involving burn residue of fresh, evaporated, and emulsified crudes have taken place on fast ice (melt pools) and in brash and frazil/slush ice conditions. Some experiments have involved residues of fresh and evaporated crudes in leads.

CHAPTER 4. APPLYING *DEEPWATER HORIZON* RESPONSE EXPERIENCE TO ARCTIC ISB

The highly successful ISB operation conducted as part of the response to the DWH incident yielded significant gains in lessons learned about the operational aspects of ISB with fire boom. This section describes how those lessons could be applied to ISB in ice-affected waters. It was compiled by interviewing personnel involved in the on-water and overall management of the burn operations in the GOM.

4.1 Optimal Deployment Strategies

The optimal deployment strategy in the GOM was driven by the nature and handling constraints of the fire-resistant boom used. This will also be true in the Arctic. Compared with conventional containment boom some fire-resistant booms are less resistant to fatigue and chafing damage, even before any exposure to high temperatures during burning operations. For this reason, two important operational guidelines have been established in order to maximize the life of the fire booms.

1. Do not deploy fire boom until conditions are right to collect and burn oil.
2. Do not retrieve fire boom until its condition is degraded to the point of being unusable, or until wind/sea conditions are predicted that could damage the boom.

Adherence to these two guidelines optimized the life of fire boom during the DWH response, enabling booms to be used for long-duration burns and re-used many times before being taken out of service. Some fire booms are susceptible to fatigue when working in heavy seas (with or without burning) and should be used only during relatively calm conditions. For burning in drift ice conditions, fatigue would be less significant, but abrasion by contact with ice floes could expose fire booms to additional abrasion wear. While some fire booms are sufficiently robust and can handle wind, waves, and extreme towing forces, even the best fire booms degrade during burning operations. All booms should be inspected against designated criteria or manufacturer specifications upon completion of a burn to ensure that additional burns can be conducted safely and with minimal loss of oil.

The most successful burn task groups include four vessels:

1. An offshore support vessel ("*OSV*"), providing accommodations for the burning crew, crane services, and working deck space for boom deployment, retrieval, and maintenance/repair (**Figures 4-1** and **4-2**; next page).
2. Boom "*towboats*" – Deployed in pairs for pair-trawling, or "*U-boom sweeping*" operations to concentrate the oil for burning. (Fishing vessels, particularly trawlers or draggers were particularly valuable for this duty in the GOM).[8]

[8] In Arctic waters the use of a single towboat with a towing paravane should be considered to make the best use of scarce vessel resources.

Figure 4-1 Aerial view of task group in oil, preparing for burn. Note the OSV at the top of the frame, and the two boom towboats handling a U-Boom sweep. The igniter boat can be seen off the port side of the port boom boat. (photo source: Elastec)

Figure 4-2 Deploying fire boom from a reel. Note the chafing gear installed underneath the boom (photo source: Elastec)

3. "*Igniter boat*" - Small, fast, low-freeboard boats to deliver igniter packages and carry out modest in-water boom repairs.
4. Instances of boom retrieval and re-deployment were extremely rare in the GOM. Instead, crews chose to leave the boom in the water and tow it to the next burn site. Boom-towing transits of 30 km (18 miles) or more were common when assets had to be repositioned

between burns. In ice-affected waters this may be suitable in light drift ice, but for transits in pack ice it would be advisable to remove the fire boom from the water to prevent damage from contact with floes. Leaving fire boom in the water at night alongside the OSV is recommended. In the GOM this was less stressful on the boom than recovering on deck; however, there were other risks. On two occasions, fire boom being tended by a towboat overnight was run over and damaged by other vessels transiting carelessly close to the boom tending boats. Boom lights can help reduce this risk, but may be difficult to attach and keep operating over extended periods.

4.2 Identifying Target Slicks for Burning Operations

Trained and experienced spotters on support aircraft were a valuable resource for moving task groups in the GOM into the heaviest concentrations of oil and should be incorporated into any Arctic ISB operation. When air support was not available in the GOM, spotting oil from vessels was difficult. When necessary, crews developed alternative techniques for finding heavy concentrations of oil. The most successful of these was to run the igniter boat on a ladder search pattern within visual range of the OSV. When the bow wave of the igniter boat turned black, a phenomenon easily recognized with binoculars, the boat was quite often in heavy concentrations of oil. Running the boat throughout that region while maintaining radio contact with the OSV enabled the observer to estimate the size and location of the oiled region.

Although no burning operations were initiated during hours of darkness in the GOM, search operations frequently continued at night. Normally, one vessel of a towboat pair would pass its towline to the second towboat which would then tend the collapsed U-boom configuration through the night. The first towboat would then conduct a search for heavy oil concentrations using high-intensity floodlights; the heavy oil concentration coordinates would be radioed back to the OSV. If the oil concentration was extremely heavy, the first towboat would often remain on location near the slick until daybreak. The rest of the task group would then get an early start toward that location and rig for daylight burning operations. This procedure enabled the burn teams to begin collecting oil while awaiting the arrival of the aerial spotters.

It should be recognized that the DWH spill was different from many other spills where burning or other high-volume removal techniques have been used; the well was located far offshore. With the support of experienced aerial spotters working from small fixed-wing aircraft (e.g., a King Air), burn teams could be guided into heavy oil for several hours before the aircraft had to return to shore to refuel. On most days, a second fixed-wing aircraft was available so that nearly continuous spotting support could be provided for 7.5 hours in spite of the long transits offshore and the need to refuel the aircraft. The efforts of aerial observers and surface crews to locate oil and guide the burn operations offshore made it possible to collect and eliminate 100’s of thousands of barrels of spilled oil with minimal resources and with very little impact upon the environment.

4.3 Refinement of collection techniques

4.3.1 Deploying Boom

Aside from burning operations, launch and retrieval of fire boom can put considerable stress on the boom as well. It may be dragged across the deck of a vessel or over a bulwark, subjecting it to chafing and small-radius bending. In the GOM, crews were trained on how to handle the fire booms to minimize damage during launch and retrieval. All OSVs were supplied with both fabric or chafing gear to lay down on the deck beneath the boom, and large diameter pipe for constructing bolsters to protect the boom as it was deployed over a deck edge, railing, or bulwark (**Figure 4-3**). Similar training and equipment will need to be incorporated into Arctic ISB plans.

Figure 4-3 Fire boom being deployed. Note pipe bolster and chafing gear beneath the boom. (photo source: Elastec)

Water-cooled fire boom had been provided on reels so that the apex (bight) of a U-configuration could be deployed first. This allowed the OSV to hang onto both towlines and cooling water lines during initial deployment. Passing the towline and hose to a towboat from the OSV is easier and safer than rigging floats and having a towboat retrieve the lines from the water. Other booms were delivered on pallets or reels allowing them to be deployed in straight-line, one-end-first manner

4.4 Collecting Oil

Pair trawling (i.e., towing with two boats in a U-configuration) is a common way of concentrating oil for a batch burn, and, if safe to do so, feeding additional oil to an ongoing burn (**Figure 4-4**). Normally, U-boom configurations are towed into the wind to keep the towboats from having to work in the smoke plume. Sweeping downwind, however, can put less stress on the boom, reduce turbulence within the contained area, and still permit a safe and effective burn as the smoke drifts at a safe height above the towboats. If there is any concern for particulate fallout, the towboats can alter their course slightly allowing the smoke to pass to either side of them. In

Arctic waters the use of a single towboat with a towing paravane should be considered to make the best use of scarce vessel resources.

Figure 4-4 Pair trawling with fire boom prior to burning (photo source: Elastec)

"*Open apex*" tactics were used in the GOM in an attempt to concentrate oil more efficiently for burning (**Figure 4-5**; next page). Two, 200 metre legs of conventional ocean boom were towed in a 'U' with a chained opening at the apex. This configuration would be positioned to deflect oil through its apex into a separately towed fire boom 'U' directly downstream. The intention was that, working together, the four boats could sweep a wider swath, concentrating oil more quickly for burning. In the GOM this approach proved difficult because the vessels available to handle the open-apex boom were large and cumbersome, and their operators were unfamiliar

Figure 4-5 Open apex sweep ahead of a fire boom sweep (photo source: Elastec)

with low-speed towing operations. Furthermore, these vessels were not very manoeuvrable and had difficulty holding station relative to one another. Although this tactic is often an effective tool in open ocean spill response, it was decided that the extra resources required to perform open-apex sweeping were not justified by the marginal increase in effectiveness. Also, the open apex application was unnecessary because the tow vessels could easily be guided into the oil windrows that were naturally created by the wind and waves.

In ice affected waters the "*open apex*" tactic would be even less effective, as the collector booms would concentrate also small ice pieces and have to manoeuvre around larger floes.

4.5 Ignition Techniques

Simple igniters were assembled from off-the shelf components for use in the GOM. They consisted of a marine signal flare, attached to floats surrounding a plastic bottle with gelled fuel (**Figures 4-6**, **4-7**, and **4-8**; next page). Once ignited the flare would burn back and melt the bottle containing the gelled fuel. This would allow the fuel to flow out of the bottle and form a pool around the flare. The released gelled fuel would ignite and heat the surrounding crude oil to its fire point. The ignition of the contained crude oil or light emulsion would normally take several minutes providing ample time for the igniter boat to move to a safe distance upwind of the burning oil. Igniter packages based on this design are now commercially available, and should be stockpiled for use in Arctic ISB operations.

Figure 4-6 Simple igniter package (photo source: Elastec)

Figure 4-7 Lighting the flare before placing the igniter in the oil (photo source: Elastec)

Figure 4-8 Placing the igniter package (photo source: Elastec)

Gasoline was used initially as the fuel in the igniters; however, it was replaced by diesel for safety and availability reasons. Diesel was gelled with a commercially-available gelling agent, providing a safe, slow-burning gel for the heating and ignition of the oil and light emulsions commonly encountered during the response. For similar reasons, the use of diesel fuel is recommended for igniting oil in fire booms in Arctic waters.

Heli-torches and other forms of aerial ignition devices were considered and disqualified as an option by planners and deemed impractical for the GOM in situ burn operations. Most burns were 75 to 95 km (40 to 50 miles) from land, and this presented a logistical problem for a shore-based Heli-torch operation. Heli-torches are deployed as slung loads, carried externally by helicopters. Flying so far offshore with a sling load would have presented an elevated risk to the aircraft and its occupants. The distance would also have limited the time available on site for ignition operations. Under existing air operations guidelines supporting production activities in the Gulf, the refuelling and supporting of Heli-torch operations from offshore facilities would not have been allowed. When surface-ignition protocols proved safe and successful, Heli-torch operations were no longer considered. The use of Heli-torches will need to be addressed for ISB operations in drift and pack ice conditions when fire booms cannot be used and slicks collected by herding agents or the wind are to be ignited. Heli-torch operations are, at present, the only technique available for igniting oil on melt pools covering a large area.

Early in the operation, igniters were deployed ahead of the fire boom and allowed to float into the contained oil. This tactic was soon substituted with the upwind placement of the hand-held igniters directly into the contained oil from igniter boats.[9] By approaching the collected oil from the upwind or side-wind region outside of the boom, and placing the activated igniter directly in the oil/emulsion, the slow heating and eventual ignition of the oil could take place safely and effectively. Ignitions were almost always successful, being accomplished with only one or two igniters. However, this success rate was significantly diminished during the last several days of the burning operation after the well was controlled and the heavily weathered and emulsified oil curtailed burning operations.

4.6 Evaluation of Oil Volume Burned

The approach used to evaluate the volume of oil burned during the DWH spill response involved aerial and surface monitoring of each burn by trained observers. Techniques were developed involving the area of the burn, an estimated burn rate of the oil based on its weathered state, and the duration of each burn. Great care was taken in observing, recording, and photographing the size and duration of each burn, including the changes in burn area from start to finish. By estimating the areas of the fires and their duration of burning, it was possible to make a reasonable estimate of the amount of oil consumed during each fire. During the response in the GOM, 376 significant burns were conducted, documented, and evaluated. Using conservative minimum and maximum burn rates, those burns are estimated to have removed between 220,000 and 310,000 bbls of oil (USCG, 2011; Mabile 2012).

The estimated volumes of oil burned during the DWH spill were calculated based on well-established burn rates for crude oil (including weathered and emulsified oil). There was no estimation of "*effectiveness*" as a measure of the amount spilled or collected in the fire booms. The burn estimates are simply conservative values for the minimum and maximum volumes of oil that were likely eliminated by combustion based on the size and duration of the burns.

Similar oil removal estimation techniques are recommended for ISB operations in Arctic waters. In the case of igniting and burning oil on melt pools in the spring, modifications will be necessary because of the large number of small, short duration burns that would be taking place at the same time.

[9] These revised protocols were developed, evaluated, and approved by industry and USCG safety personnel for this response.

4.6.1 Boom Performance

The reader should refer to the BP report on ISB operations during DWH (Mabile, 2010). According to the report, three[10] different fire boom products were used extensively. Two were passive systems, and one was actively cooled. The findings include:

- The actively cooled booms used inflatable flotation. As one would expect, the reel-packed inflatable boom took up a small fraction of the storage space required by the booms relying on solid flotation.
- All three were found to be readily deployable, though the inflatable, water-cooled boom was reported to have offered '*speed, simplicity and stress reduction during deployment and recovery*.' One of the non-water-cooled, solid flotation booms was reported to provide, '*simplicity of use and a range of options for storage and transport*.'

The report stated succinctly that, 'For fire boom to be effective, it has to contain oil floating on water before, during, and after exposure to … burning ….' It concluded that:

- 'The more rigid construction booms did not have as good a wave response' while the water-cooled inflatable boom 'maintained a high level of containment integrity for extended periods of time … .'
- By contrast, '*Booms with ceramic [solid] flotation became less capable of retaining oil with each burn*.' The relative flexibility and wave-following capability of the inflatable boom system worked in its favour to retain more oil.
- Furthermore, the fence-type boom 'would tend to suffer during towing as the fabric would tear easily …. The structural integrity was subject to compromise after repeated burns, but could often be controlled by alternating the most intense portions of a burn to different sections of a U-configuration.'
- Field repairs were needed to prolong the life of all fire boom used. Mabile (2010) reported that the water-cooled inflatable boom was easily recovered for repairs or repaired in-water. Its component construction allowed replacement of the flotation bladders and water-cooled covers.
- A high buoyancy-to-weight ratio was prized in the report because it reflected the general sea-keeping capability of the boom. With the highest buoyancy-to-weight ratio of the three booms used (more than 6 to 1), Mabile (2010) reported that the inflatable, water-cooled boom '*exhibited good sea keeping abilities which extended the operating window when sea conditions deteriorated*.'
- Fire booms for use in Arctic waters will need all of the desirable qualities noted above, and will also need to be resistant to: abrasion, failure when contacting ice, and capable of operating in sub-zero temperatures.

4.6.2 Feasibility of Burning Emulsions

Although a comprehensive sampling programme was not undertaken to characterise the emulsification of the oil, the burn team believed that emulsions of high water content were burned on many occasions. The success of the burns of emulsified oil was due in part to the

[10] Products from two additional manufacturers were used, but both failed early in trial burns, and were removed from service (Mabile, 2010).

amount of less-weathered/emulsified oil collected at the same time.[11] The intense heat generated during a burn seemed to help break emulsions contained within or fed to an ongoing burn. The burn team concluded that the burning of these emulsions was practical (subject to the actual water content), but that such burns with similar emulsions in the future will require larger igniter kits and favourable weather conditions for ignition and sustained combustion.

4.6.3 Collection of Burn Residue

Collection of post burn residue was not required by the Unified Command (Government and industry representatives who oversaw the response) because it was felt that it was more important to return fire booms to service collecting and burning more oil than it was to delay and devote resources to recovering the residue. Residues were characterised as thick, semisolid masses that broke up and dispersed quickly after cool-down. Observed mechanisms of residue dissipation included dispersion and submergence, usually within minutes to an hour after a burn was extinguished.

11 Both fresher, unemulsified oil and more weathered and emulsified oil were collected in the same fire boom; the fresher unemulsified oil ignited and burned and the heat generated from its burning helped the more emulsified oil to break and burn.

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