
STUDIES OF IN-SITU BURNING OF EMULSIONS IN NORWAY

Chantal C. Guénette, Per Sveum, Cathe M. Bech
SINTEF Applied Chemistry, Environmental Technology
N-7034 Trondheim
Norway

Ian A. Buist
S. L. Ross Environmental Research, Ltd.
717 Belfast Road
Ottawa, Ontario K1G 0Z4
Canada

An experimental program, spanning four years, was initiated in 1990 to study the in-situ burning of emulsions. Its main objectives were to study the in-situ burning of emulsions in dynamic conditions (wind, waves, currents, and ice); to define the limitations and effectiveness of in-situ burning in terms of water content, evaporation, and film thickness of crude oils and emulsions; and to determine the physical processes involved in burning water-in-oil emulsions. Field experiments were conducted in basins cut into sea ice ranging in size from 4 m² to 300 m². Small-scale pan burns and emulsion-heating experiments were conducted in the laboratory. The results show that evaporated water-free oil can be easily ignited and burned with a high efficiency, even in the presence of swells and slush ice. When water contents exceeded 25 percent, the emulsions were difficult to ignite using gelled gasoline, and could not be ignited in the presence of moderate swells. However; ignition could be improved by using alternative igniters. Some postulated processes on the burning of stable emulsions have been confirmed: water must be removed from the emulsion surface before ignition can occur, water is released mainly through evaporation, and the temperature in the emulsion slick does not seem to exceed the boiling point of water.

In-situ burning is one of the most promising techniques for rapid removal of large quantities of spilled oil at sea, in ice infested waters, and in snow and as a disposal technique for recovered oil and emulsions. Recent work has demonstrated the feasibility of these applications of in-situ burning.;SU1 - 3,8,9 Most recently the Newfoundland offshore burn experiment (NOBE) trials have demonstrated the feasibility of in-situ burning at sea.⁶

This program, initiated by the Norwegian Clean Seas Association for Operating Companies

(NOFO) in 1990, started with a literature review of in-situ burning and was followed by extensive experimental work in the field and the laboratory. Through experiments carried out in recent years as part of the NOFO Arctic program, it became clear that the processes controlling in-situ burning of emulsions were different from those controlling in-situ burning of unemulsified oils on water. At least it became clear that the emulsion burning process had to be more complex - involving several more steps than the burning of unemulsified oil. While ignition and burning of a crude oil slick is predominantly governed by the slick thickness, other factors affect the success of this technique including the properties of the oil at the time of ignition - particularly the degree of emulsification - meteorological and oceanographic conditions, and the availability of the oil.

As part of this program of in-situ burning of emulsions, a series of small- and meso-scale in-situ burning field experiments were conducted on Spitsbergen in 1991, 1992, and 1993 and laboratory experiments were conducted in 1993.

Materials and Methods

Field experiments.

All field experiments were carried out on the frozen fjord near Sveagruva on Spitsbergen, Norway, during the months of April and May of each year. Environmental conditions during this period were typical of springtime in the Arctic, with temperatures ranging from -20 to 0 ° C and wind speeds from calm to 15 m/s. The ice thickness in the fjord, which varies from one year to another, was on average greater than 1 m thick. The experimental basins were constructed in the fjord by cutting and removing blocks of ice.

Small-scale field experiments, 1991 and 1992.

These experiments were conducted in circular basins with an area of 4 m² and a depth of 30 cm. The freeboard of the ice in the basin was approximately 10 cm. To maintain a constant water level in the basins, an overflow system was designed (Figure 1). In addition, during the 1992 experiments, basins with areas of 20 m² were constructed to study the effects of scale.



1.

Small-scale basin with overflow system used for the 1991 field experiments - The basin had an area of 4 m² and a depth of 30 cm.

The oils used for the 1991 experiments were blends obtained from the Statoil refinery in

Norway (Mongstad) and were composed of a mixture of Statfjord and Gullfaks crudes in a ratio of 4:1. Various degrees of weathering were simulated by using different cuts of these oils and were characterized according to the content of the following petroleum products: heavy naphthalene, kerosene, light gas oil, heavy gas oil, buffercut, and residue. The oils used in the 1992 experiments were a mixture of marine gas oil, heavy diesel, fuel oil No. 6LS, and fresh Statfjord/Gullfaks. The composition of each experimental oil is given in Table 1 along with its physical and chemical properties.

The experimental design for the small-scale experiments is given in Table 2. Experimental series I to VI were conducted in 1991, while series VII to IX were done in 1992.

Meso-scale field experiments, 1992.

The meso-scale experiments were conducted in an open basin cut in the fjord ice, measuring 10 × 30 m. The freeboard of the ice in the basin was approximately 10 cm. The inside of the basin was lined with logs to minimize melting of the edges during the experiments. A hydraulically powered wave machine was mounted in the ice along the short side of the basin to study the effect of waves on ignition and burning. The waves generated during these experiments were approximately 30 cm in height and 3 m long.

A total of six burn experiments were conducted in this basin, each with 4,000 L of oil or emulsion. The effect of emulsion water content, the amount and type of ice in the basin, waves, winds, and ignition source were evaluated. Fresh oil and emulsions containing 12.5 and 25 percent water were used in these experiments. The effect of waves, both on ignition and the burning processes, was evaluated. The ignition sources investigated were gelled fuels (gasoline, diesel, and crude oil) and layers of fresh crude or the 250+ cut of Statfjord crude oil.

Laboratory experiments, 1993.

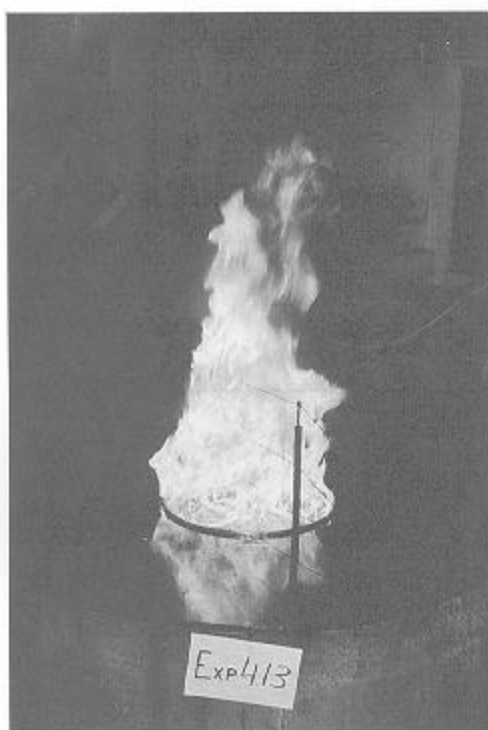
Two types of laboratory experiments were conducted: small-scale burns of crude oil and emulsions on water and static emulsion heating experiments where the oils and emulsions were heated but not ignited. These experiments evaluated conceptual models of the emulsion burning process developed following the previous years' experiments,^{2,3} and studied the effectiveness of different ignition sources for water-in-oil emulsions, building on the gelled gasoline concept.

The small-scale burning experiments were conducted in a water-filled circular pan 120 cm in diameter and 32 cm in height (Figure 2). Removable rings 40 and 75 cm in diameter were used to contain the oil or emulsion to be burned. Thermocouples were placed in the flames, slick, and underlying water to measure temperatures during the experiments. Burn efficiency, burn rate, ignition time, and the physical and chemical properties of burn residue were studied as a function of oil type, degree of evaporation of the oil, amount of water in the emulsion, and the initial slick thickness.

The oils used for the small-scale burns were Statfjord, Alaska North Slope, and Avalon crudes. The initial properties of these oils are given in Table 3. The oils were artificially evaporated by sparging compressed air into the bottom of a 205 L drum containing the oil. The Avalon and Alaska North Slope oils were evaporated to approximately 10 and 20 percent loss by volume and Statfjord crude oil was weathered to 13, 20, and 31 percent loss by volume. Emulsions were created by mixing the required

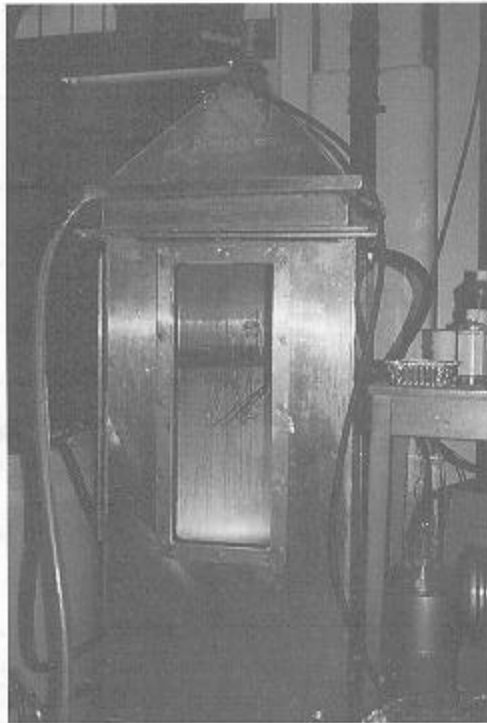
volumes of saltwater and crude oil with a high energy impeller mixer until a stable emulsion was obtained. Emulsions with water contents of 12.5, 25, 40, 60, and 75 percent water by volume were created for the laboratory burn experiments.

The static emulsion heating experiments were conducted in a specially designed apparatus for measuring temperature gradients in heated oil and emulsion slicks on water. Oil and emulsions were subjected to a constant heat flux using a radiant heat source placed above the slick. The experiments were designed to investigate the relationship between emulsion slick properties (slick thickness, emulsion water content, degree of evaporation, and heat transfer through the slick), and how these affected the physical and chemical changes occurring in the emulsion when heated. The apparatus consisted of a 0.5 m by 0.5 m by 1.4 m high aluminum box with a detachable lid and two viewing windows on the sides (Figure 3). Two heating elements were installed in the lid providing a maximum energy output of 3,000 watts. Air from this sealed system was purged using nitrogen to prevent ignition of the oil vapors. Thermocouples were placed throughout the emulsion layer to measure slick temperatures during the experiments and logged temperatures at 15 second intervals. The slick layer was sampled periodically during the experiments using sample ports fitted with syringes located on the side of the box. The samples, taken from various depth of the slick, were analyzed for density and water content.



2.

Setup for experimental laboratory burns - The slick was contained in a 40 cm diameter ring centered in a 1 m diameter pan of water. Three thermocouples measuring temperatures in the flames are shown.



3. *Apparatus for studying heat transfer through oils and emulsion slicks on water* Small-scale field experiments, 1993.

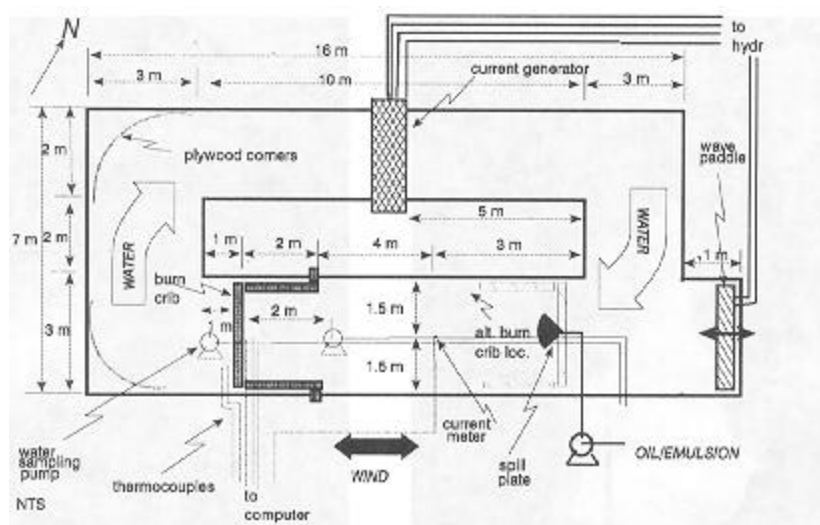
Following the small-scale laboratory burns, designed to evaluate some suggested improvements to the gelled gasoline igniter, small-scale field experiments were conducted to further test the proposed igniter concepts under more rigorous conditions. The recommended improvements to the existing igniter technology (gelled gasoline) arising from the laboratory work were evaluated during a series of 12 small-scale burns. The effectiveness of gelled crude oil and the addition of emulsion breakers and ferrocene (a combustion enhancer and soot reducer produced by Chemische Betriebe PLUTO) to the gelled crude oil were investigated in these experiments.

The experiments were conducted in 4 m² square basins cut into the fjord ice. For each experiment, 200 L of emulsion was used. The effectiveness of the igniter was assessed using emulsions of Statfjord crude, weathered to 18 and 25 percent evaporated by volume and emulsified with 12, 25, 50, and 60 percent seawater by volume. The igniters, consisting of 100 mL of gelled fresh crude with the various combination of additives, were contained in small plastic bags and placed directly onto the slick before ignition. A propane torch was used to ignite the igniters.

Meso-scale experiments, 1993.

Experiments were conducted in a circulating flume to investigate the ignition, combustion, and residue remaining from a continuous burning of weathered crude oil and emulsion against a barrier. Of particular interest was whether or not heat radiated from a fire could ignite otherwise unignitable emulsions drifting toward the burn and whether or not the residue might eventually become neutrally

buoyant or perhaps sink.



4.

Schematic of the circulating flume basin built in ice and used for field experiments of emulsion burning against a barrier

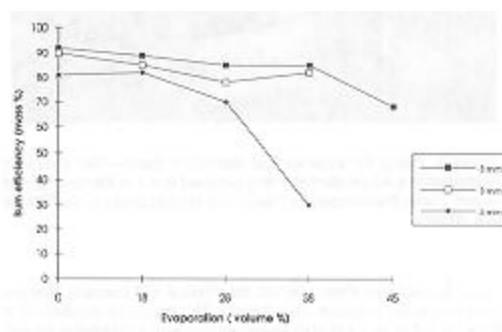
The circulating flume was built in the fjord ice as shown in Figure 4. The overall basin dimensions were 7 by 16 m. The channel widths were 3 m wide on three sides of the basin and 2 m wide on the long side which was fitted with a current generator. A wooden crib served to contain the burning slick along the 3 m wide channel parallel to the channel with the current generator. A wave machine was installed at the upstream end of the channel containing the burn crib.

For each experiment, 100 L of 18 percent evaporated Statfjord crude was pumped into the barrier. With the current generator set for a current of 0.3 m/s, an initial slick area of approximately 6 m² could be maintained. After ignition of this oil, the emulsion was pumped into the flume and allowed to drift towards the burning slick.

Results and Discussion

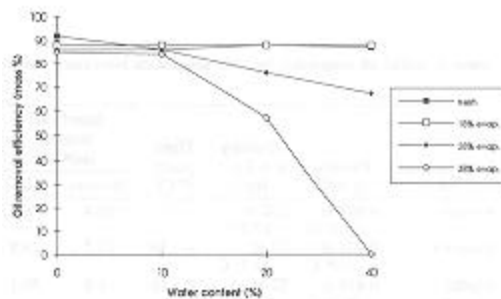
Limitations and effectiveness of burning. Small-scale field and laboratory experiments have provided a basis for evaluating the limitations and effectiveness of in-situ burning of oils and emulsions in terms of evaporation, water content in emulsions, and initial slick thickness. In the first three series of small-scale field experiments, burn characteristics of unemulsified oils were studied at initial slick thicknesses of 4 and 8 mm. Figure 5 shows the burn efficiency of Statfjord crude oil at different degrees of evaporation (defined as the volume percent of oil removed). In the experiments conducted with initial slick thicknesses of 8 mm, the burn efficiency ranged from 80 to 90 percent for oils with degrees of evaporation of less than 45 percent. Burns with 45 percent evaporated oil showed a decrease in burn efficiency to approximately 70 percent. A decrease in initial film thickness from 8 mm to 4 mm resulted in a decrease in burn efficiency to approximately 80 percent for fresh and 20 percent for evaporated crude oil, and to 70 and 30 percent for the 28 and 38 percent evaporated oils, respectively. High winds, in the order of 9 to 10 m/s had a negative effect on some of the burn parameters. A decrease in

burn efficiency and increase in slick thickness at extinction were noted. The effects on ignition time, flame spreading, and burn rate are more ambiguous. For some experiments, the wind effect on these parameters was positive, while on others it was negative. The burn efficiencies, expressed as a percentage of oil removed from emulsions, are given in Figure 6. The burn efficiency of emulsions made with fresh and 18 percent evaporated oil did not appear to be affected by the water content. The more evaporated oils showed a decrease in burn efficiency when emulsions contained 20 and 40 percent water. At all degrees of evaporation, except for fresh crude, emulsions containing 40 percent water required a higher initial slick thickness for successful ignition. Emulsions made with 18 and 28 percent evaporated oil were ignited and burned with efficiencies in the same range as the lower water content emulsions when the initial slick was approximately 40 mm thick. Ignition of the 38 percent evaporated oil (with a water content of 40 percent) was successful at a slick thickness of 32 mm; however, burning was not sustained and only a small portion of the emulsion was removed.



5.

Burn efficiency of Statfjord crude at different degrees of evaporation



6.

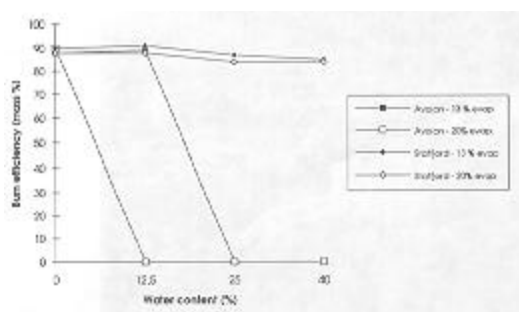
Burn efficiency of Statfjord crude oil at different degrees of emulsification

The general trends observed during these experiments were that the burn efficiency of oils and emulsions decreased with increasing degree of evaporation and increasing water content. The burn rate decreased both with increasing degree of evaporation and water content. For water-free oil, the rate decreased from 3 mm/min for fresh crude to 1.4 mm/min for evaporated oil. Also, high winds (9 to 10 m/s) tended to decrease the burn rate. The ignition time (time for the area around the igniter to catch fire) for evaporated oils was under 90 seconds and did not appear to be affected by slick thickness. Fresh oil ignited instantaneously. Emulsions made from fresh crude ignited in 25 to 30 seconds. Emulsions made of oil evaporated to 28 percent or less and with water contents of up to 20 percent water

required up to 60 seconds for ignition to occur. It was not possible to ignite emulsions of oil weathered to 18 percent or more with a water content of 20 percent using a gelled crude oil igniter. Flame spreading decreased with increasing evaporation and emulsification. Flame spreading over fresh oil was approximately four times faster than that of the more evaporated oils. Similar observations were made with emulsions of fresh crude and of evaporated crude. Flame spreading of the 38 percent evaporated crude emulsions was very slow, and close to zero when the water content was 40 percent.

Similar trends were also observed during the laboratory burns with three different oils (Avalon, Alaska North Slope, and Statfjord crudes) and are consistent with findings reported elsewhere.^{4,5,8} The laboratory experiments also indicated that oil type is a factor in the way emulsions burn. During these experiments it seemed that the initial chemical and physical properties of an oil can affect which emulsion properties will have a greater impact on the burn parameters. Figure 7 compares the burn efficiency of Avalon and Statfjord crude oils over various degrees of evaporation and emulsification. The initial slick layer was 10 mm and the ignition source was a gasoline-soaked sorbent pad. It can be seen that water content had a strong effect on the ignitability and burn efficiency of Avalon, while Statfjord showed little dependency on water content at these degrees of emulsification. The burn efficiency of Statfjord decreased with increasing water content when the degree of evaporation was 30 percent. The Avalon emulsions containing up to 25 percent water, shown in this figure, could be ignited using a 1 mm or 2 mm layer of fresh oil, and they burned with similar efficiency as the lower water content emulsions.

A statistical analysis of data obtained from over 200 small-scale laboratory burns supports these findings. A multiple regression analysis was performed to study which factors influence central burn parameters. For all three oils studied, the burn efficiency was significantly dependent on the initial slick thickness, the amount of water in the emulsion, and the degree of evaporation. Avalon showed a higher dependency on the emulsion water content than the other oils. The burn efficiency decreased more rapidly with increasing water content in Avalon burns. The burn rate was significantly affected by the emulsion water content for all oils. The burn rates of Avalon and ANS were significantly affected by a combined slick thickness/water factor, while the degree of evaporation was a significant factor for Avalon alone. For all oils studied, the ignition time, time to intense burn, and the extinction time were all significantly dependant ($P > F = 0.05$) on the initial slick thickness.



7. *Comparison of burn efficiencies for weathered Avalon and Statfjord crude oils*

Burning process of emulsions.

It became evident after the first series of emulsion burns, that the burning process for emulsions was different from that of unemulsified oils. As a result of these experiments, a conceptual model of emulsion slick burning was postulated by Bech Sveum, and Buist.^{2,3} It was postulated that it is not the emulsion that burns, but rather a layer of oil floating on top of the emulsion supports combustion. For ignition of an oil slick to occur, the heat supplied by an ignition source must be sufficient to raise the temperature of the adjacent slick surface above the oil's fire point (the temperature at which the concentration of volatile hydrocarbon gases remains high enough to support combustion). The controlling factor in ignition and burning of emulsions appears to be the removal of water from the emulsion. It was theorized that the maximum temperature that a water-in-oil emulsion reaches is the boiling point of water. Once the water is removed, oil is released, forming a layer of water-free oil on the emulsion surface. This water-free oil layer can then be volatilized and ignited given that a sufficient heat source exists. The sustained burning of an emulsion slick will depend on a continuous and dynamic water removal process. Water can be removed from an emulsion in two ways: boiling the water out of the slick or breaking the emulsion thermally or chemically. Indications from the experiments suggest that with stable emulsions, the water is released by boiling it out of the emulsion. In the case of unstable emulsions, thermal breaking might be possible.

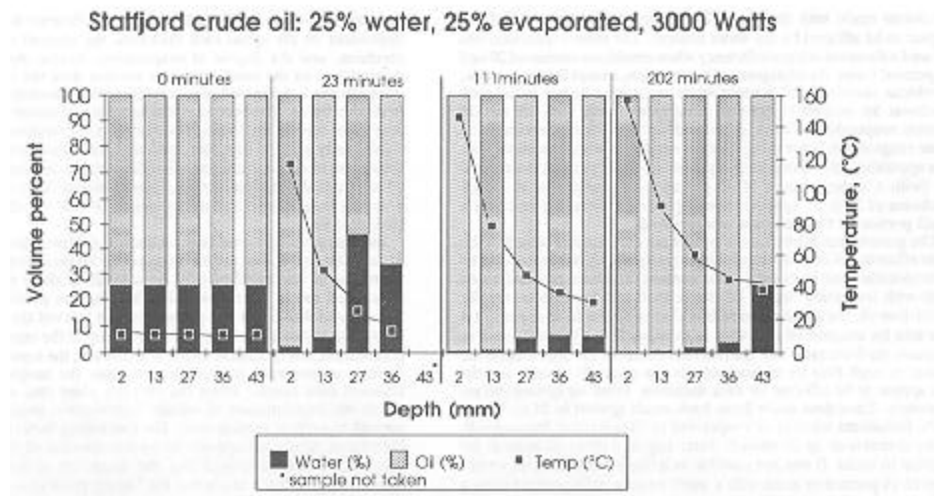
Temperatures recorded during the field and laboratory burns, as well as the emulsion heating experiments, support this conceptual model. Figure 8 shows the temperature development and water content in an emulsion layer during an experiment conducted in the heat transfer apparatus. A fairly steep temperature profile exists in a heated emulsion. As the water is evaporated from the emulsion slick, the temperatures increase. Temperatures decrease quickly below the surface of the slick where the water content is higher. The temperature at a given location in the slick does not exceed 100 °C until the emulsion water has been removed.

The conceptual model was also supported by visual observations. Steam was observed rising from the slick surface during emulsion burns. A phenomenon typical of emulsion burning is foaming at the slick surface, which may also be related to the water loss mechanism. Foam is created by the intense mixing of a gas and a liquid containing surface-acting chemicals that stabilize the thin film of the liquid around the gas bubble. In the case of burning emulsions that foam, the gas is probably steam (with some combustion by-products and air) and the liquid is probably oil. Foaming may be initiated by the development of a condition of increased pressure in the liquid water in the emulsion. Foaming is often followed by the extinguishment of the burning slick. Typically, foaming will occur over one section of a slick, temporarily extinguishing the fire locally by either smothering, insulating the oil layer, or a combination of the two. After the foam breaks, if another area of the slick is still on fire, the affected area can re-ignite and burn. This may occur several times before the slick finally stops burning.

In-situ burning in dynamic conditions.

The meso-scale experiments evaluated the use of in-situ burning under more realistic and rigorous conditions. In 1992, a total of six experiments were conducted in a 300 m² basin to study the effect of swell, wind, and ice conditions on in-situ burning of crude oil and emulsions. These experiments were conducted using 4,000 L of either water-free oil or emulsions containing 12 and 25 percent water.

The effect of waves was evaluated during the ignitions and the steady burn phase. Waves had a negative impact on the ignition and burning of emulsions, while there was no negative effect on the burning of water-free oils. Water-free oils could be burned to a 90 percent efficiency when waves were present during both the ignition and the burning phases. None of the attempts to ignite the emulsions in the 300 m² basin with waves was successful. Emulsion slicks ignited under calm water conditions, could be extinguished by starting the wave machine and inducing wave movement in the basin, and resulted in burn efficiencies of 50 percent. Under calm conditions, a 25 percent water-in-oil emulsion burned with an 80 percent efficiency.

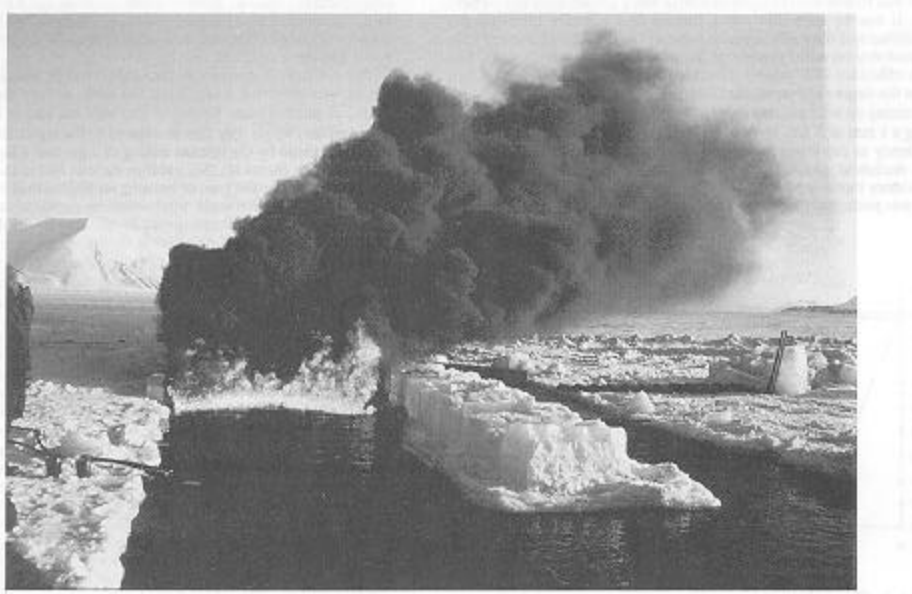


8.

Temperature development and water content in an emulsion layer - Each section of the graph gives the oil and water fraction of the emulsion, and the temperature as a function of depth for a given time of sampling.

The 1993 field experiments studied the ignition, combustion, and residue remaining from continuous burning of weathered crude oil and emulsions against a barrier (Figure 9).⁷ In these experiments, emulsions with water contents of 12 to 50 percent were carried by a 0.3 m/s current into a burning 18 percent evaporated oil slick contained against a barrier. The feed rate of the emulsion into the flume was approximately 15 L/min. A burn area of approximately 6 m² was maintained during the steady burn phase giving an estimated average burn rate of approximately 2 mm/min. The ignition time for the forward edge of the emulsion slick was estimated to be one minute following contact with the contained burning slick. As the cold emulsion drifted into the burning slick, it flowed under the hot oil where it was warmed to the point where water was evaporated, indicated by the steam seen rising from the emulsion slick. Shortly thereafter, this section of the emulsion slick was covered in flames. Emulsions with higher water contents released more steam during this warming phase. During the second flume experiment, with a 25 percent water-in-oil emulsion, the wave maker was turned on during the steady burn phase, creating swells of approximately 10 to 15 cm in amplitude and 3 to 4 m in length. The waves did not affect the ignition of the emulsion drifting into the burning slick. It would appear that the heat radiated from the burning slick was sufficient to overcome any dampening effect the waves may

have had on the ignition. These waves did not decrease the intensity of the burn or the burn area. Emulsions with 50 percent water were successfully ignited using this technique in winds of up to 10 m/s and in currents of 0.3 m/s. Burn efficiencies for these experiments were estimated to be above 90 percent.



9.

Burning emulsions against a barrier in a circulating flume built into the ice on Spitsbergen

The theories on the burning process of emulsions may offer an explanation for the emulsion burning behavior observed during these two series of experiments in dynamic conditions. Emulsion burning appears to be a dynamic steady-state process dependent on the rate of water-free oil supply to the slick surface being equal to or greater than the rate of volatilization of the oil. This process will be sensitive to slight reductions in the thickness of the water-free oil, much as in-situ burning of unemulsified oils is dependant on a minimum slick thickness. Wave action may affect or restrict the evaporation of water or the distribution of a water-free oil layer on the emulsion surface. At the crest of a wave, the water-free oil layer may become too thin to support combustion, causing the slick to be extinguished in that area. However; if the amount of heat added to the system is sufficiently high to generate water-free oil in excess of what is required to maintain a high enough temperature in the oil film at the wave crest, then emulsions can theoretically be burned in the presence of waves. This needs to be verified experimentally. In the case of experiments conducted in the 300 m² basin, the swells were larger than those generated in the circulating flume. In addition, the slick in the circulating flume was herded and contained against a barrier, therefore maintaining a relatively thick slick. It is possible that a layer of water-free oil could be maintained under these conditions even in the presence of waves. While the swells in the flume basin were smaller than those generated in the large basin, the fact that the burn did not extinguish in these waves may indicate that the ignited slick was providing sufficient heat to not only sustain burning of the contained emulsion but to ignite the emulsion drifting into the burn.

Burn residue.

The fate and behavior of burn residue was observed during the circulating flume experiments. Most of the burn residue remaining from each experiment could be contained by the barrier, although some loss did occur particularly in the presence of waves. While loss of residue beneath the barrier occurred throughout the burns, the majority of the loss occurred towards the end of each burn. In general the residue remained buoyant, floating just below the surface of the water with portions of the residue above the waterline. Some residue was observed circulating around the basin approximately 30 cm below the surface. Much of the residue lost during the steady burn phase of these experiments was recirculated back into the burning slick and could be reignited. It was estimated that about 25 percent of the lost residue was submerged below the water surface, but remained buoyant and was transported around the flume basin by the current. The physical and chemical property analysis of the burn residue revealed that although the viscosity of the burn residue was orders of magnitude higher than the initial oil or emulsion, the density did not increase beyond 0.97 g/cm³. The density of the residue in these experiments therefore remained below that of seawater. Theoretically, this would indicate that residue is unlikely to sink; however, the flume experiments showed that residue can be carried beneath a barrier by a current and that residue can remain neutrally buoyant or become submerged below the water surface.

Igniter sources.

In the 1991 field experiments, 400 mL of gelled gasoline (25 g Surefire gelling agent/1,000 mL gasoline) was initially used as the igniter for the experimental burns. This ignition method proved effective with fresh and evaporated oils, but ineffective with oils evaporated more than 18 percent and with a water content of greater than 25 percent. Conclusions from the work performed in 1991² were that for oils evaporated more than 18 percent and with a water content above 20 percent, gelled gasoline was insufficient as an igniter and one capable of generating more heat was required. Liquid and gelled crude oil proved to be better igniters for the emulsions because of the higher temperature at which they burned.

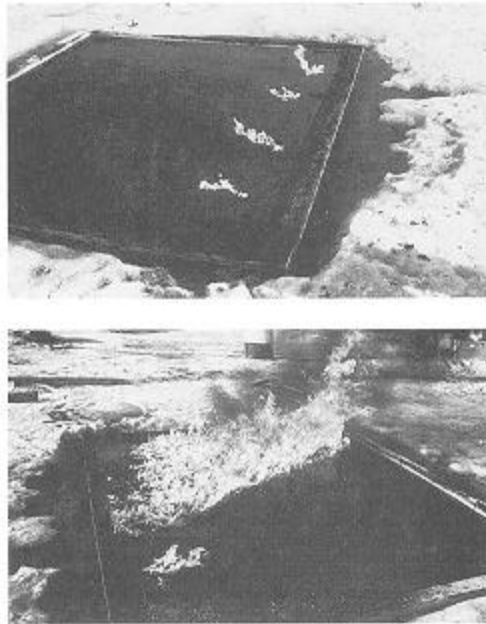
Limitations of the gelled gasoline and gelled crude oil igniter concept were investigated during the 1993 laboratory experiments, and attempts were made to improve upon this technology. Experiments were conducted with emulsions of Statfjord, Alaska North Slope, and Avalon crude oils. The addition of emulsion breakers and ferrocene to gelled gasoline and gelled crude oil was also evaluated. The laboratory experiments showed the use of gelled crude oil to be more effective than gelled gasoline, and the addition of these additives to further enhance the ignition capabilities of both the gelled gasoline and gelled crude oil. The crude oil igniter, having shown the greatest potential in the laboratory experiments, was chosen for further evaluation and development during the 1993 field experiments.

Figure 10 shows the experimental setup in the field used to evaluate potential gelled crude oil igniters. Gelled crude oil (100 mL of fresh Statfjord crude) and combinations of emulsion breaker and ferrocene were mixed in a plastic bag which was then placed on an emulsion slick. The experiment compared various concentrations of emulsion breaker. Experiments were conducted with Statfjord crude oil emulsions containing 12, 25, 50, and 60 percent water. The experiment demonstrated that the

addition of emulsion breakers to the gelled crude oil igniter resulted in greater ignition and flame spreading over this 50 percent water-in-oil emulsion slick. The lower photo in Figure 10 shows the slick area ignited by the crude oil igniters containing emulsion breaker. The gelled crude oil on its own (lower left hand corner of this photo) was not as effective.

Conclusions

Some general conclusions can be made from this emulsion burning program.



10.

Comparison of demulsifier concentration in gelled crude oil igniters - The igniter that did not contain a demulsifier appears at the bottom of the lower photograph.

- Evaporated water-free oils can be easily ignited and burn with high efficiencies. These oils also burn efficiently in the presence of swells.
- Swells in the order of 30 cm in height and 3 m in length can reduce the burn efficiency of emulsions and make ignition impossible. Heat radiated from a fire could ignite emulsions of Statfjord crude oil containing 50 percent water, drifting towards an ignited slick in a current of 0.3 m/s and in waves up to 15 cm high.
- The residue generated from burning oils and emulsions can be entrained underneath barriers, but remains neutrally buoyant in seawater. The density of burn residue was shown not to exceed that of seawater.
- Gelled crude oil was an effective igniter for emulsions containing less than 50 percent water. The addition of emulsion breakers to this igniter enhanced ignition capabilities and the rate of

flame spreading over the slick surface.

Acknowledgments

This program has been jointly funded by the Norwegian Clean Seas Association for Operating Companies (NOFO), Alaska Clean Seas (ACS), Marine Spill Response Corporation (MSRC), Chemische Betriebe PLUTO, and Amoco Eurasia. The authors would like to acknowledge the contributions and advice of Aage Bjørn Andersen and Widar Skogly of NOFO, Bruce McKenzie of ACS, James Simmons of MSRC, Christian T\uolle of PLUTO, Nick Vanderkooy of Amoco, and Jack R. Gould. We would also like to thank the Store Norske Spitsbergen Kullkompani and the Governor of Spitsbergen for their support during the experimental field work.

References

1. Allen, A. A. and R. J. Ferek, 1993. Advantages and disadvantages of burning spilled oil. *Proceedings of the 1993 International Oil Spill Conference*, American Petroleum Institute, Washington, D.C., pp765 - 772
2. Bech, C., P. Sveum, and I. Buist, 1991. In-situ Brenning av Emulsjoner. SINTEF Report No. STF21 F91081. Trondheim, Norway
3. Bech, C., P. Sveum, and I. Buist, 1993. In-situ Brenning av Emulsjoner II: Effekt av Oppskalering og Effekt av Bølger. SINTEF Report No. STF21 F93031. Trondheim, Norway
4. Cabioc'h, F., 1993. Last French experiments in order to evaluate the burning possibilities of three water-in-oil emulsions. *Proceedings of the 16th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*. Environment Canada, Ottawa, Ontario, pp823 - 832
5. Energetex Engineering, 1980. A Study to Evaluate the Combustibility and Other Physical and Chemical Properties of Aged Oils and Emulsions. Report for Environment Canada, Ottawa, Ontario
6. Fingas, M. F., K. Li, F. Ackerman, M. C. Bissonnette, P. Lambert, G. Halley, R. Nelson, P. R. Campagna, R. D. Trupin, M. J. Trespalacios, J. Bélanger, J. R. P. Paré, and E. J. Tennyson, 1994. The Newfoundland in-situ oil burn experiment - NOBE. *Spill Technology Newsletter*, v18, n2, pp1 - 10
7. Guénette, C., P. Sveum, I. Buist, T. Aunaas, and L. Godal, 1994. In-situ Burning of Water-in-Oil Emulsions. SINTEF Report No. STF21 A94053. Trondheim, Norway
8. S. L. Ross Environmental Research, 1989. Disposal of Spilled Hibernia Crude Oils and Emulsions: In-situ Burning of The Swirlfire Burner. Report for Canadian Coast Guard, Ottawa, Ontario
9. Sveum, P., C. Bech, and M. Thommasen, 1991. Experiments and implementation in a Norsk Hydro drilling contingency plan. *Proceedings of the 14th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, Ontario, pp399 - 410

Table 1. Physical and chemical properties of the Statfjord/Gullfaks oil mixtures

Initial

Oil type ₁	Density (g/mL)	Viscosity at 13 °C (cp)	boiling point (° C)	Composition ₂ (% volume)
Fresh crude	0.846	10.9	n/d ₃	HN(5), kero(12), LGO(15), HGO(7), buffercut(5), residue(30)
150+	0.881	102	134	HN(6), kero(16), LGO(20), HGO(10), buffercut(7), residue(41)
200+	0.883	87.7	193	Kero(17), LGO(25), HGO(10), buffercut(17), residue(44)
250+	0.902	429	241	LGO(26), HGO(12), buffercut(9), residue(53)
300+	0.921	n/d ₃	256	HGO(16), buffercut(12), residue(72)
250+	0.935	529	n/d ₃	Marine gas oil (20), FSD (10), fuel oil No. 6LS (13)
"250+"	n/d ₃	n/d ₃	n/d ₃	250+ (80), Statfjord/Gullfaks (7), marine gas oil (13)

1. used in 1991, upper section of table; used in 1992, lower section

2. HN = heavy naththaline; kero = kerosene; LGO = light gas oil; HGO = heavy gas oil; FSD = heavy diesel

3. not determined

Table 2. Experimental design for the 1991/92 small-scale field experiments

Experiment	Oil type	Water content (%)	Initial slick thickness (mm)	Wind velocity (m/s)
I	crude, 150+ - 300+	0	8	2 - 5
II	crude, 150+ - 250+	0	8	9 - 10
III	crude, 150+ - 250+	0	4	2 - 5
IV	crude, 150+ - 250+	10	8	7 - 8.5
V	crude, 150+ - 250+	20	8	10 - 11
VI	crude, 150+ - 250+	40	8	
VII	250+	0,10	8	5 - 6
VIII	250+	20, 30, 40	8	5 - 6, 4 - 7, 5 - 6
IX	"250+"	25	35	

Table 3. Initial oil properties for 1993 small-scale laboratory burns

Experimental oil	Density (g/cm ³)	Viscosity at 6.5 s ⁻¹ (cp)	Flash point	Interfacial tension (mN/m)	
				(° C)oil/water	air/oil
Avalon	0.883 at 14.1 ° C	230 at 13.5 ° C	-3	16.4	38.9
Statfjord	0.844 at 13.0 ° C	17 at 12.3 ° C	<-10	21.7	29.8

Alaska	0.878 at	22 at	<-10	4.0	30.1
North Slope	16.1 ° C	14.1 ° C			
