IN-SITU BURNING OF UNCONTAINED CRUDE OIL AND EMULSIONS

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ABSTRACT

Large scale field experiments were carried out on Spitsbergen during the fall of 1994 to investigate the feasibility of burning Statfjord crude oil and emulsions uncontained on open water. Previous work on a smaller scale had shown that the self-induced wind herding effect of the burning slick can reduce spreading and that very high oil removal efficiencies can be obtained. Findings from emulsions burning process studies have revealed, among other things, that the temperature of emulsified oil does not exceed that of the boiling point of water while burning studies. It was postulated that the lower temperatures, and consequently higher viscosities, maintained in an emulsion layer during in-situ burning, might further reduce spreading of the slick.

Findings from these large scale experiments support both the wind herding effect and the cooler emulsion layer theories, and are presented in this paper. Burn efficiencies for uncontained fresh crude oil ranged from 80% to 92% for initial slick volumes of 500 L to 8000 L. Burn efficiency for 50% water-in-oil emulsions ranged from 65% for an initial volume of 2000 L to approximately 75% for an initial volume of 4000 L. Uncontained burning emulsions spread much more slowly and to a lesser extent than fresh oil slicks.

INTRODUCTION

Over the past few years a number of studies have addressed many issues related to using in-situ burning as a response to oil spills on water; however, few have investigated the possibility of burning crude oil uncontained. As with other spill response techniques, the effectiveness of in-situ burning is limited by the slick thickness. Typically, a 1 mm slick thickness is needed for ignition and sustained burning of fresh or lightly evaporated water-free oil, while slick thicknesses of 3 to 5 mm are required for ignition of emulsions and heavier oils (Twardus 1980). The greater the initial slick thickness, the greater the oil removal efficiency. It is considered that in the absence of natural containment, other means must be used to maintain a slick thickness favourable for burning. The need for artificial containment of an oil slick can be a costly and time consuming step in responding to marine spills. The possibility of burning a slick uncontained would offer a simple alternative to the logistically demanding task of containing spilled oil.

It has been proposed that large, uncontained crude oil spills on water could burn with high removal efficiencies, given a high enough initial slick thickness. The high burn efficiencies observed during a number of spills which have accidentally caught fire have suggested the feasibility of burning slick uncontained (e.g.: Turbini *et al.* 1993). The idea of uncontained burning is based on the premise that the self-induced

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wind herding effect of the combustion air drawn in around the edges of a burning slick will prevent the slick from spreading as quickly as an unignited slick. One study on the in-situ burning of uncontained oil slicks reported high burn efficiencies for fresh crude oil burning uncontained and an average net inflow of air of approximately 0.14 m/s around the periphery of a contained slick (S.L. Ross and Energetex 1986). The burning crude oil slicks were found to spread less quickly than a non burning slick. These findings supported the theory of self-induced wind herding effect inhibiting the spread of oil and creating conditions permitting in-situ burning.

Results from emulsions burning experiments carried out in previous years by SINTEF Applied Chemistry suggested that emulsified oils may offer an even greater potential for uncontained burning because of their inherent burning characteristics. Among the findings from a series of extensive laboratory and field experiments, carried out to study the emulsion burning process, were the following: a layer of water free oil must be formed on the emulsion slick surface before ignition can occur; emulsions water is removed mainly through evaporation; and the temperature in a burning emulsion slick does not exceed the boiling point of water, resulting in a steep temperature gradient across the slick. (Bech *et al.*, 1992, Sveum and Bech 1992, and Guénette *et al.* 1994). With these lower slick temperatures, and consequently higher slick viscosities, it is was believed that an emulsion slick would not spread as quickly nor as thinly as would an unemulsified slick. Burning uncontained emulsions was therefore thought to be feasible and it was of interest to evaluate this possibility on a large scale.

This paper presents the main findings from a series of experiments undertaken to determine the feasibility of burning crude oil and emulsions uncontained, and validate some of the proposed theories on uncontained burning. The study was undertaken as part of a larger project on in-situ burning of emulsions, which also included burning emulsions in broken ice and the development of an emulsion breaking igniter. The issues of particular interest in this part of the project were:

- feasibility of burning crude oil uncontained
- spreading of burning crude oil on water
- effect of emulsification on uncontained burning
- removal efficiency for fresh and emulsified oils

MATERIALS AND METHODS

Experimental set-up. A series of large scale uncontained burning experiments were carried out during the fall 1994 in a lagoon located across the fjord from Sveagruva on Spitsbergen, Norway. The lagoon measured approximately 1.3 km long by 800 m at its widest point. Apart from a narrow channel, the lagoon was entirely enclosed, minimizing the possibility of any loss of oil or residue to the main fjord. Water temperatures in the lagoon during the test period were approximately 0 to 4°C, and ambient air temperatures ranged from 0 °C to 5°C. The average wind speed was between 4 and 6 m/s. The salinity in the lagoon was approximately the same as that measured in the fjord, 35 parts per thousand. The experimental site is shown in Figure 1.

The oil or emulsion to be burned was released into a floating steel ring measuring

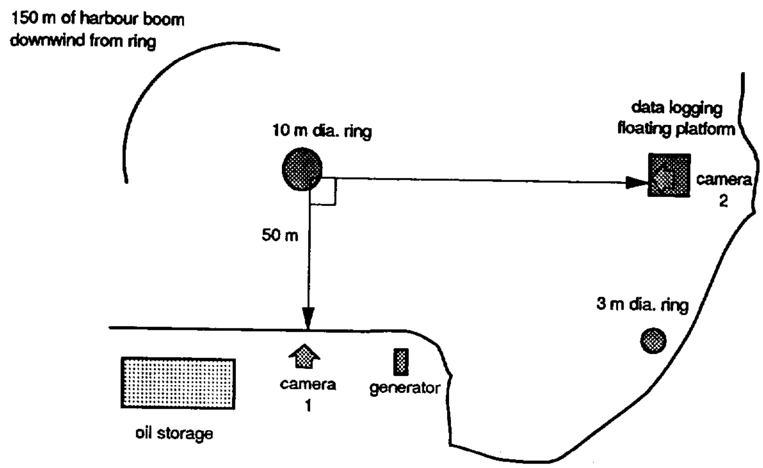

Figure 1. Experimental site for uncontained burning experiments

10 m in diameter and 0.5 m in height. The surface area inside the ring was approximately 80 m^2. The ring was anchored to the bottom of the lagoon using sand filled oil drums and connected to a winch on shore used to position the ring at the desired level at the water surface and to lower the ring to release of the burning slicks. The ring was located approximately 50 m from the nearest shoreline. The containment ring and release mechanism are shown in Figure 2. The test oil was pumped into the ring from shore using a 400 L/min pump and a floating plastic pipe.

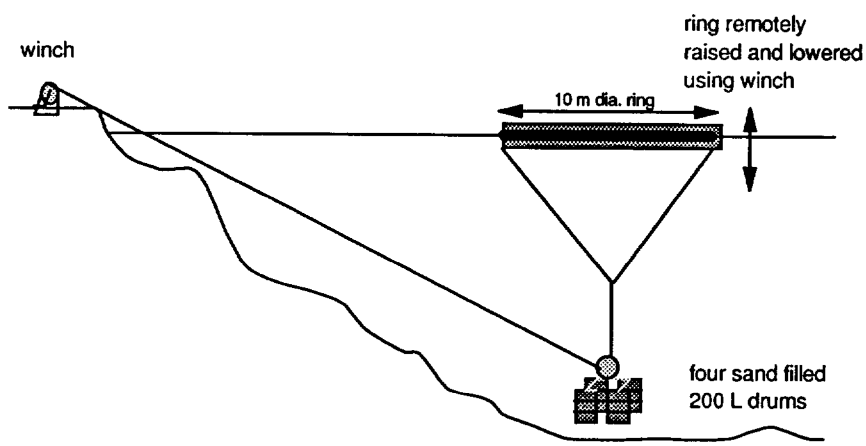

Figure 2. Containment ring and slick release mechanism

A small cabin was set-up on a floating platform from where wind speed and direction were logged, and video recordings taken. Two video cameras were positioned perpendicular to each other to record the spreading of the burning slicks during these experiments.

The fresh oil slicks were ignited using a burning gasoline and crude oil soaked sorbent and released once the entire surface was covered in flames. The igniter was place in the upwind end of the slick. The emulsions were ignited using emulsion breaking igniters deployed from a Helitorch (Guénette and Sveum, 1995). Ignition of approximately 75 to 80% of the slick surface had occurred before releasing the emulsions.

Residue and any oil which might have escaped from the ring before an experiment was collected in the 150 m of oil containment booms placed approximately 100 m downwind from the ring. Following each burn, the burn residue was allowed to drift into these booms. The boom ends were then brought close together to form an narrow "U" shape and contain the burn residue. Residue was collected from a work boat using pumps, shovels and pitch forks, depending on the properties of the residue.

Test oil and emulsions. Statfjord crude oil was used for these experiments. The initial oil and emulsion properties are given in Table 1. Fresh Statfjord crude was evaporated in 4.4 m^3 and 12 m^3 cylindrical tanks to approximately 25% evaporative loss by volume, by sparging a known volume of oil with compressed air. During the air stripping process, the contents of the tank were recirculated using a pump with a flow rate of 400 L/min. This caused the temperature of the oil to increase to roughly 50°C. The loss of volume due to evaporation was determined by measuring the height of the oil in the tank. Stable emulsions were created by mixing the 25% evaporated oil with natural seawater in a large tank using a high capacity pump.

Table 1. Initial properties of Statfjord crude oil.

Evaporation (vol. %)	Water content (vol. %)	Density (g/cm^3)	Viscosity (cP)	Shear rate (s^{-1})
0	0	0.838 at 21°C	81.9 at 15°C	12.24
25	0	0.871 at 25°C	1250 at 13°C	4.0
25	51	0.959 at 20°C	4500 at 13°C	4.0

Density and viscosity analysis of the oils and emulsion were done according to standard ASTM methods, using an Anton Paar densitometer and a Brookfield viscometer. Emulsion water content was determined by chemically breaking the emulsion and measuring the volume of released water.

RESULTS AND DISCUSSION

A total of seven meso-scale experiments were carried out during the 1994 summer field session on Spitsbergen. Four burns were carried out with fresh crude oil, ranging in volume from 0.5 m^3 to 8 m^3 and three emulsions burns with volumes of 1.2, 2 and 4 m^3 were attempted. Table 2 summarises the parameters for each experiment and some of the results. Because of difficulties in igniting the emulsion in experiment U4, the slick was not released. The thickness given in this table is the initial slick thickness of the oil or emulsion contained in the 10 m diameter ring prior to its release. The burn efficiency for the fresh oil is given as percentage oil removed from the water surface. The residue recovered following the emulsion burns contained some unburned emulsion and burn residue of varying water content. It was therefore simplest to express the emulsion burn efficiency as the percentage of emulsion, rather than oil, removed from the water surface.

Table 2. Summary of uncontained burn experiments with fresh and 50% water-in-oil emulsions of 25% evaporated Statfjord crude oil

Exp. No.	Oil type	Volume (L)	Initial thickness (mm)	Wind speed (m/s)	Ignition time (min:sec)	Burn efficiency (%)	Burn time (min:sec)	
							Total	Uncontained
U1	fresh	500	6.25	2.4	1:43	80	3:52	2:12
U2	fresh	1000	13	1.8	0:45	80	3:35	2:50
U3	fresh	3 000	37.5	3.2	0:50	85	5:40	4:10
U4	emulsion	1 200	15	4.1	-	<10	10:31	-
U5	emulsion	2 000	25	4.0	(8:10)	65	14:10	7:20
U6	fresh	8 000	100	0.4	2:42	92	10:15	7:45
U7	emulsion	4 000	50	0.1	(13:30)	75	27:00	13:30

( ) includes time used to drop igniters

Ignition. Ignition of the fresh oil slicks was done using a gasoline and crude oil saturated sorbent, set on fire with a propane torch and dropped onto the upwind end of the slick. The ignition time given in Table 2, is the time required for the entire area inside the ring (80 m^2) to become covered in flames. The 0.5 m^3 slick required roughly twice as much time as the 1 and 3 m^3 slicks to achieve full ignition. This is consistent with observations made during previous work (Bech *et al.* 1991). Because of the lower insulating capacity of the thinner slick, the time required to heat the oil to its fire point is higher, resulting in a lower flame spreading rate. Almost three minutes were needed for full ignition of the 8 m^3 slick. A shorter ignition time would have been expected, however, a change in wind direction occurred almost immediately after the igniter was dropped onto the slick. The igniter was therefore at the downwind end of the slick for this experiment. Ignition and released of the 8 m^3 slick are shown in Figures 3 and 4.

Figure 3. Ignition of 8 m^3 fresh Statfjord in 10 m diameter ring

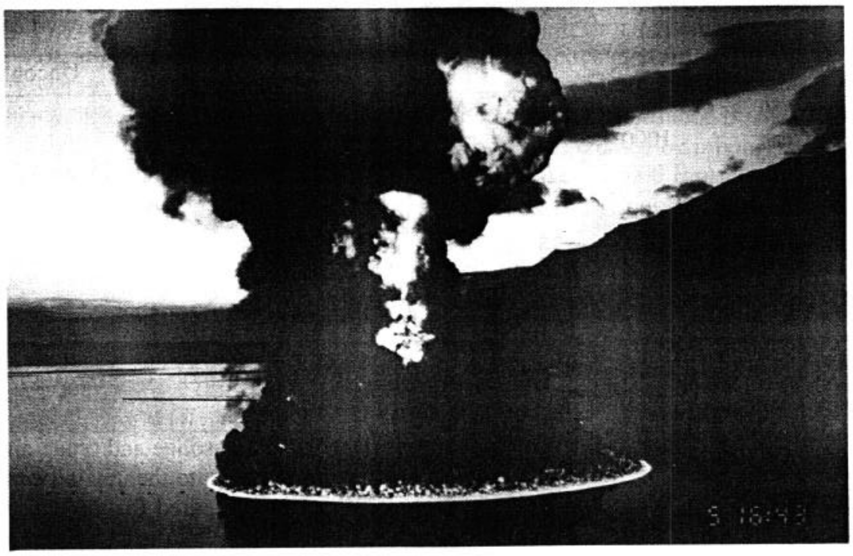

Figure 4. Uncontained burning of 8 m^3 fresh Statfjord crude oil

The uncontained emulsion burning experiments were carried out in conjunction with testing of an emulsion breaking igniter developed during an earlier phase of this project. Three emulsion burning experiments were planned,; however, only two of the emulsion slicks were released. In the first emulsion burn, high winds (2 to 8 m/s with gust of over 10 m/s) made deployment of the igniters difficult and prevented full ignition of the slick. Only about 10% of the slick surface, near the ring edge, was ignited and remained burning for approximately 5 minutes. The slick was therefore not released in this experiment. In the following two emulsion experiments, the igniter was more effectively deployed and ignition of approximately 75 to 80% of the slick surface had occurred before releasing these slicks. Figures 5 and 6 show the ignition and release of the 2 m^3 emulsion slick.

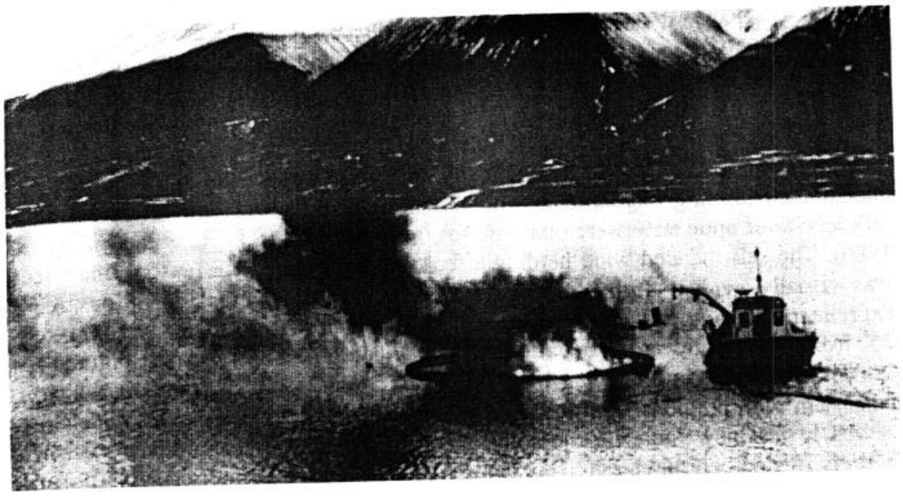

Figure 5. Ignition 2 m^3 of a 50% w/o emulsion of Statfjord crude oil in the 10 m diameter ring

Figure 6. Uncontained burning 2 m^3 of a 50% w/o emulsion of Statfjord crude oil

Burn efficiency. The estimated burn efficiencies for fresh and emulsified Stafjord crude oil burning uncontained are given in Figure 7. As observed with the contained burns conducted during previous laboratory and field experiments (Bech *et al.* 1991, 1992 and 1993, Guénette *et al.* 1994, and Guénette and Sveum 1995), the burn efficiency increased with increasing volume for both fresh oil and emulsions. Burn efficiency for fresh crude oil ranged from 80% for an initial volume of 0.5 m^3 to 92% for an initial volume of 8 m^3. The burn efficiency obtained for a contained burn of 8 m^3 fresh Statfjord crude oil done during the winter field session was 99%, compared with a burn efficiency of 92% for an uncontained burn of the same volume (Guénette and Sveum 1995). This would indicate that, although uncontained, the slick maintained a thickness which could support combustion. This is likely due to the self-induced wind-herding effect, which can oppose the spreading force of the slick, thus reducing the spreading rate. Similar observations were made during previous uncontained burning experiments with initial slick diameters of 6 m where burn efficiencies of up to 91% were observed for fresh crude oil (S.L. Ross and Energetex 1986). The self-induced wind herding effect was believed to the reason This effect was visually evident during the burns carried under very calm conditions (e.g.: experiments U6 and U7). also be observed. A pronounced flame angle, approximately 75° from vertical, toward the centre of the slick could be observed (see Figure 4).

The emulsions burned with lower efficiencies than the fresh crude oil, which is consistent with previous results. During these experiments in particular, which also served to test new igniter technology, the fact that the emulsion slicks were not entirely ignited before release likely contributed to the low burn efficiency. The burn efficiencies were approximately 65 and 75% for initial emulsion volumes of 2 and 4 m^3 respectively, but could likely have been higher had the igniters been more effectively deployed. Nevertheless, these experiments demonstrated that fresh crude oil and emulsions can be burned uncontained with reasonably high removal rates.

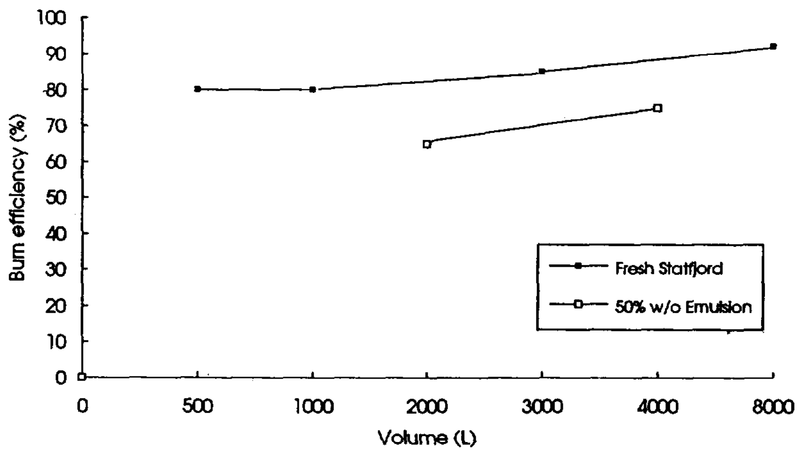

Figure 7. Burn efficiency of uncontained fresh crude and 50% w/o emulsion of 25% evaporated Statfjord crude oil. Initial slick diameter was 10 m.

Flame spreading. Figures 8 to 9 show the flame spreading in two directions (perpendicular) for the fresh oil and emulsion burns respectively. Flame spreading was estimated using the video recordings taken during each experiments. The 0.5 m^3 fresh oil slick burning slick spread to its maximum diameter of 12 m in less than 20 seconds following its release. A sheen or very thin slick of oil surrounding the burning slick of approximately 15 m in diameter was observed. This sheen was assumed to have been too thin to support combustion and presumably measured less than 1 mm in thickness. The sheen was visible throughout the remainder of the burn. As it was difficult to distinguish between the slick and the flame area during the following burns, spreading of the burning slick only will be discussed.

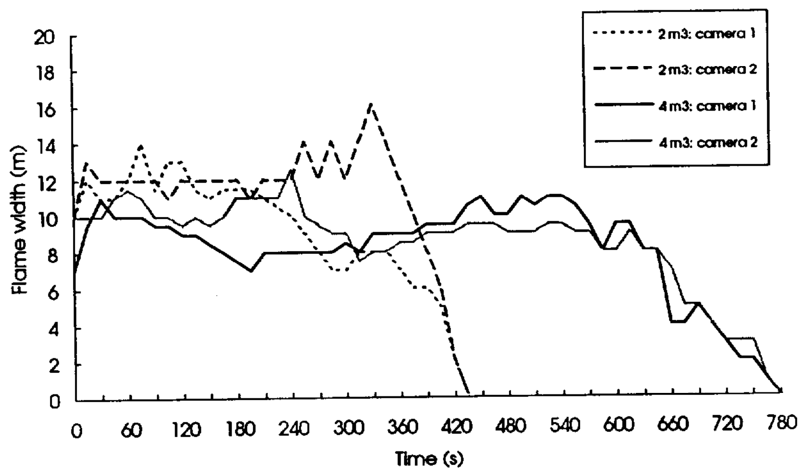

Figure 8. Flame spreading for uncontained burning of fresh Statfjord crude oil

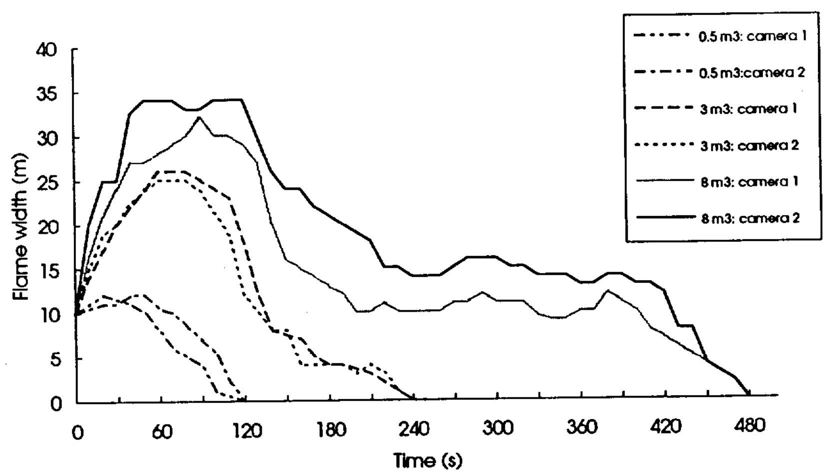

Figure 9. Flame spreading for uncontained burning of 50% water-in-oil emulsions

The flame area for fresh oil and emulsion experiments is given in Figure 10. The flame area was calculated based on the assumption that the burning slick was elliptic in shape. It can be seen from Figure 8 that the fresh oil slicks quickly spread to their maximum width, in approximately 60 seconds or less. The spreading rate increased with increasing volume, as indicated by the increasing steepness of the slopes on this graph. The maximum flame area for the 3 m^3 burn was roughly 510 m^2 while the 8 m^3 burning slick spread to an area of approximately 850 m^2. The 3 m^3 slick began to decrease in size about 30 seconds after reaching its maximum dimension. The 8 m^3 slick remained near its maximum width for just over one minute, then receded to between 10 and 15 m in dimension over the course of the following few minutes, where it remained during most of the burn. In the case of fresh oil, the decrease in flame area appeared to occur at a similar rate as the flame spreading observed during the beginning of the burn. The flame area decreased rapidly until a certain point when there seemed to be a pause and stabilization of the flame area until very close to the end of the burn. This behaviour was more pronounced in the largest burn.

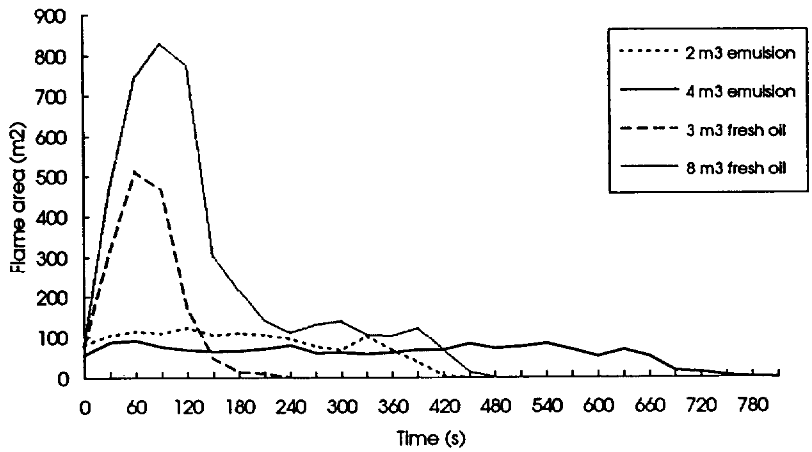

Figure 10. Flame area for fresh crude oil and 50% w/o emulsions burning uncontained

With the emulsion burns, the maximum width was reached after approximately the same amount time as the fresh oil burns, however the slick size during both the 2 and 4 m^3 burns remained close to this maximum until several minutes before the end of the burn. The maximum flame area observed during the 2 m^3 emulsion burn was approximately 130 m^2, while the maximum flame area for the 4 m^3 burn was 90 m^2. The 2 m^3 burn may likely spread to a greater extend than the 4 m^3 burn due to the wind conditions on the day of the experiment. The average wind speed during the 2 m^3 burn was 4.0 m/s compared to only 0.4 m/s during the larger emulsion burn. In Figure 8 an increase in flame width of the 2 m^3 emulsion slick was observed from one camera after approximately 240 seconds, while a decrease was observed from the other. The is likely due to the strong winds during this experiment, causing the slick to stretch in one direction. This effect was also observed during other burns.

Unlike the fresh oil slicks, the burning emulsion slicks did not decreased in size shortly after the maximum flame area was reached. The spreading curves for the emulsion burns remain relatively flat during most of the burn. Figure 9 depicts a periodic fluctuation in flame width during both emulsion burns, with slick dimensions increasing and decrease around the maximum point reached initially. This observation lends credence the theory that water is evaporated from the emulsion slick, producing a layer of water free oil on the slick surface which can then be vaporized and the vapours burned. The periodic expansion of the slick area observed during these experiments may be due to the water free oil released from the slick burn spreading over and beyond the edges of the underlying emulsion slick. This water-free oil would have a lower viscosity than the emulsion and thus spread over a greater area than that covered by the emulsion slick. Spreading of this water free oil would be limited mainly by the self-induced wind-herding effect. Burning of this oil would continue until the slick layer becomes to thin to support combustion. Heat loss through the slick is greater for portions of the oil laying on water than on the emulsion slick, because of the insulating effect of the oil contained in the emulsions. The oil lying around the edges of the emulsion slick would therefore extinguish sooner that the oil burning on top of the emulsion. At this point the flame area recedes to that of the emulsion.

It is evident from these graphs, that the emulsions do not spread as quickly, nor as much as the fresh oil when burning uncontained. In the case of a fresh oil slick, as the oil layer is heated by the fire, the slick temperature increases and the viscosity of the slick decreases. The main resistance to spreading occurring during the fresh oil burns is the self-induced wind herding effect of the combustion air drawn into the slick. The temperature of an emulsion slick will not increase to beyond that of the boiling point of water. This means that the viscosity of the emulsion will remain higher than that of the unemulsified oil and therefore have a greater resistance to spreading. This factor, combined with the self-induce wind herding effect may offer an explanation for the limited spreading observed with the burning emulsions. The low spreading rate of the emulsion resulting from higher slick viscosities supports some of the postulated processes occurring during emulsion burning (Bech *et al.* 1993 and Guénette *et al.* 1994).

Figure 11 shows the 4 m^3 emulsion slick towards the end of this burn. The slick has separated into two, after burning for 10 minutes uncontained. This was also observed during some of the other experiments, especially the larger ones. The break-up of the slick was usually preceded by a horseshoe formation of the slick.

Residue. The residue was contained in booms located approximately 100 m downwind from the burn. Residue recovered from the fresh oil burns was generally thick and tar like. This residue could be quite easily recovered using pitchforks and shovels. Residue from the 8 m^3 burn was particular thick and brittle in some areas, typical of highly efficient burns. Large mats of residue in the order of several square meters in area could be pick up by hand as one entire sheet.

Residue from the emulsion burns on the other hand, varied greatly in consistency, from very thick and tar like residue, to unburned oil and emulsion. Recovery of this residue was not so simple, as the viscosity was too low for shovel and pitch forks to be very effective. A large pump, with a capacity of 400 L/min, was found to be effective in this case.

Figure 11. Slick break up towards the end of the 4 m^3 emulsion burn

CONCLUSIONS

The main conclusion from these experiments was that uncontained burning of crude oil and emulsions is feasible if the slick is sufficiently thick, and in the case of emulsions, if a large enough area can be ignited.

Fresh oil:

- Burn efficiencies for uncontained fresh crude oil ranged from 80% for an initial volume of 500 to 92% for an initial volume of 8 000 L.
- Fresh crude slicks spread to their maximum width approximately 60 seconds following their release. The largest burn (8000 L) spread to a maximum width of 34 m, from an initial diameter of 10 m.
- Burn residue remaining from fresh oil burns consisted of very viscous, thick and tar like mats or lumps, typical of highly efficient burns. It could be quickly and easily recovered using pitchforks and shovel. Entire mats with areas of one to two square meters could be recovered or picked up by hand.

Emulsions:

- Burn efficiencies for 50% water-in-oil emulsions of 25% evaporated Statfjord crude oil ranged from 65% for an initial volume of 2 000 L to approximately 75% for an initial volume of 4 000 L.
- Spreading of burning emulsion slicks was significantly less than that of a burning fresh crude oil slicks.
- The residue collected after these emulsion burns varied from very viscous and tar like, to unburned emulsion. The less burned residue was difficult to collect with pitch forks and shovels because of the low viscosity. A large pump (400 L/min) could effectively recover this type of residue.

RECOMMENDATIONS

- The experiments have shown that uncontained burning can be feasible under certain conditions. Further experiments to study the effect of environmental conditions and type of release (batch or continuous) are recommended.
- Some interesting observations were made during the emulsion burns, particularly the fluctuations in slick dimension over the course of these burns. It is believed that this is related to the release of water-free oil from the emulsion, which due to its lower viscosity, flows to the outer edges of the slick. As a continuation of the emulsion burning process studies, it would be interesting to study this more closely.
- Research should be devoted to developing effective methods of recovering the burn residue. Although residue represents only a small percentage of the initial spill volume, for very large spills, or for emulsified oil which may not burn as efficiently, it would be useful to have a quick and effective recovery system.

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