IN-SITU BURNING OF CRUDE OIL AND EMULSIONS IN BROKEN ICE

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ABSTRACT

Field experiments were carried out on a frozen fjord on Spitsbergen, Norway, to determine the feasibility of conducting in-situ burning operations in a marginal ice zone. Large scale burns (4 to 10 m^3 in oil volume) were conducted with fresh and emulsified crude oil in a 15 m diameter basin partially filled with ice. A series of smaller basins were excavated in the ice a short distance downwind from the large basin and contained crude oil at various degrees of evaporation and emulsification to study flame spreading. During several of these experiments, a large steel tower, representing a platform structure was placed inside the basin. This structure was instrumented to measure temperatures, heat loads and heat fluxes during a crude oil fire as part of a safety related study.

INTRODUCTION

The experiments described in this paper were carried in 1994 on Spitsbergen as part of a wider a wider NOFO (Norwegian Clean Seas) "Oil spill contingency in Northern and Arctic Water" (ONA) which began in 1988. Within the NOFO plan, in-situ burning was considered as one of the more promising oil spill response options for ice infested waters, such as the marginal ice zone of the Barents Sea. The first three years of this programme were aimed at studying the impact of environmental conditions and state of the oil on in-situ burning and thereby defining some of the limitating conditions of burning. The effect of wind, waves, slick thickness, water content of the oil and the effects of slush ice were studied (Bech *et al.* 1992 and 1993, Guénette *et al.* 1994). Findings from these experiments indicated that ignition was difficult when wind speeds exceeded 10 m/s, particularly when the oil was highly weathered or emulsified. Emulsion were found to be increasingly difficult to ignite with increasing water content and evaporation. Waves had little impact on the ignition and burning of fresh and weathered oil, but impeded or prevented ignition of stable emulsions.

One of the limitations of recovery techniques for floating oil is effective containment of the slick. In-situ burning is also subject to this constraint, as a minimum thickness is required for ignition and sustained burning of the slick. This minimum thickness varies depending on the type of oil, the degree of evaporation and

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the degree of emulsification. Natural containment of spilled oil can occur in broken ice. The presence of ice can reduce the impact of two processes affecting the oil slick: spreading and weathering. At higher ice concentrations, oil will spread more slowly than it would in open water. When ice coverage is lower, spreading can still be reduced by the effect of wind herding. Oil herded by wind, can concentrate against ice floes and can accumulate to thicknesses capable of supporting combustion. Wave action is dampened in ice-infested waters, which also reduces the energy available to emulsifiy the oil.

During the 1993 field experiment "Experimental oil-in-ice spill in the Barents Sea" carried out by SINTEF for NOFO, involving the release of 30 tonnes of fresh Oseberg crude, it was observed that oil weathered more slowly and to a lesser extent in ice than it would have in open water (Sørstrøm *et al.* 1994). Of particular interest was the fact that the oil did not emulsifiy to the extent it would have been expected to, had the spill occurred in open water. After approximately 10 days, samples of the oil showed that it had lost 20% of it volume due to evaporation, and that it had formed a 20% water-in-oil emulsion (by volume). These results indicated that oil spilled in such conditions, could feasibly be treated using in-situ burning techniques. Burning was in fact, evaluated as the best response method available for this particular spill situation. Another recent study evaluating different response methods for several possible spill scenarios for this region concluded that in-situ burning would likely be the most effective option under certain circumstances (Vefsnmo *et al.* 1996).

The 1994 field experiments which took place on Spitsbergen were a part of a joint-effort between two separate divisions of the SINTEF group: SINTEF Applied Chemistry and SINTEF NBL (Norwegian Fire Research Laboratory). There were therefore two research projects carried out within this experimental field programme. The focus of Applied Chemistry's project. "In-situ Burning of Emulsions IV" (Guénette and Sveum, 1995) was on the use of in-situ burning as a countermeasure technique for oilspill clean-up on water. The NBL division's project, "Fire on the Sea Surface" (Wighus and Lønvik, 1995) was aimed at studying the fire hazard in the event of major oil leaks or spills in connection with oil production offshore, with emphasis on fire behaviour and thermal impacts from fires on the sea surface. Although the aims of each project were different, the same experiments could be used, providing the opportunity to share the logistics and costs of carrying out large scale burns and to maximize the information gained from these experiments.

OBJECTIVES

The objective of this study was to investigate flame spreading characteristics of burning oil and emulsions in broken ice. Of particular interest was the effect of wind on the flame spreading from one slick area to another slick area, either directly connected to, or physically separated from the main burn area.

The main goal of the Fire on the Sea Surface project was to determine the thermal environment produced by a crude oil fire on the sea surface and the response of a steel construction to the heat exposure from the fire.

EXPERIMENTAL SET-UP AND METHODS

The field experiments were carried out during the months of April and May of 1994 in the fjord near Sveagruva on Spitsbergen. Ambient temperatures were typical for this time of year, ranging from -20°C to +5°C. Wind speeds ranged from 5 to 15 m/s, with some occasional calm periods with relatively no wind. The ice thickness in the fjord was approximately 1 m at the experimental site.

The large scale burn experiments were carried out in a 15 m diameter (approx. 180 m^2 in area) basin, shown in Figure 1. The basin was built in the frozen fjord by excavating the sea ice. Ice was added to, or removed from, the basin depending on the desired ice coverage. Slush ice and sheets of ice of various sizes and shapes formed naturally over the course of the experimental period. The basin contained slush ice and ice floes ranging in size from approximately 0.5 to 3 m in diameter.

Several smaller basins, were excavated 1.5 and 3.5 m downwind from the large basin as shown in Figure 2. These basins measured 0.5 by 1.5 m and were approximately 0.5 m deep. A hole was drilled in the bottom using an ice auger to flood the basins. A 10 mm thick layer of crude oil at different degrees of weathering was placed in these basins.

During some of the burns, an instrumented steel tower representing a platform structure was placed inside the basin (see Figure 3). The tower, which floated vertically inside the basin, measured 1 m in diameter and a total of 15 m in height, 8 m of which were above the water line. A 3 m high steel pipe was positioned on top of the tower, to hold thermocouples for measuring smoke and flame temperatures. At 5 levels above the sea surface, 2 m long steel pipes were extended horizontally, carrying thermocouples and other measurement probes. The tower itself was equipped with an array of thermocouples to measure steel temperatures of the inner surface. Heat flux densities inside the fire plume were measured directly using water cooled total heat flux meters and a water cooled radiative heat flux meter. These flux meters measured total influx to a cooled object surrounded by flames. The tower could be positioned anywhere inside the basin using a system of cables and winches.

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	12.25
18	0	0.868 at 21°C	125 at 13°C	4.0
18	20	0.871 at 21°C		
25	0	0.876 at 19°C	1250 at 13°C	4.0
25	51	0.959 at 20°C	4500 at 13°C	4.0
25	66	0.974 at 20°C	6800 at 13°C	4.0

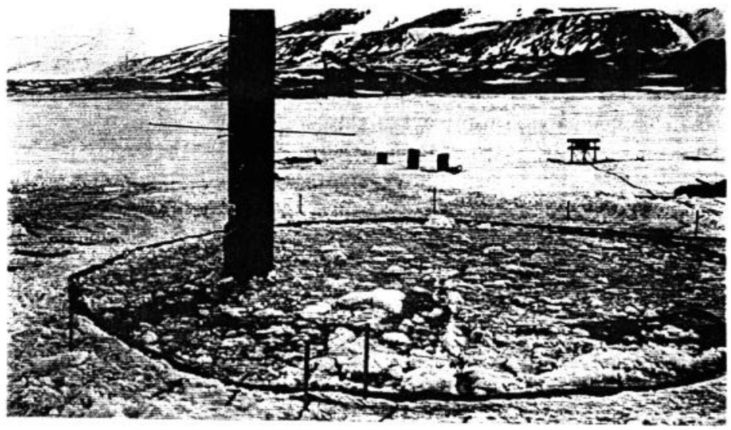

Figure 1. Set-up for burning in broken ice experiments: 180 m^2 basin with slush ice, ice floes and the instrumented tower.

Figure 2. Small (1 m^2) basins with fresh, weathered and emulsified oil downwind from large basin.

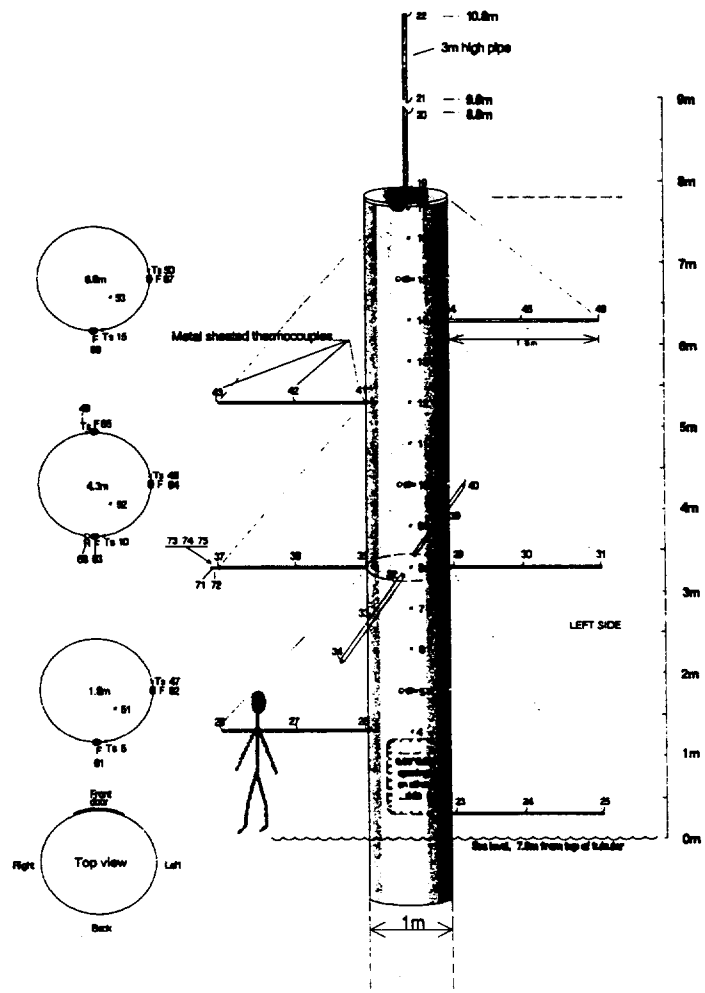

Figure 3. Steel tower instrumented to measure temperatures and heat fluxes. The total tower hight was 15 m, 8 m of which were above the water line.

RESULTS AND DISCUSSION

Burn parameters and conditions. Table 2 summarizes the experimental conditions and parameters for these experiments. Ice coverage was estimated at the beginning of each experiment and is expressed as a percentage of the total basin area. A propane torch or a gasoline soaked sorbent pad was used to ignite the fresh oil burns. An emulsion breaking igniter were tested during the emulsion burns (Guénette and Sveum, 1995).

The initial slick thicknesses and burn rates are rough estimates, due to the presence of ice in the basin. It is likely the oil and emulsions pumped into the basin spread unevenly. The slick thickness was therefore not uniform. In some areas, the oil or emulsion flowed over thinner ice floes, both as it was pumped into the basin and as the slick spread after it was ignited. The slick thickness was estimated by dividing the initial slick volume by the estimated area covered by the slick. In the case of emulsions, the slick thickness includes the emulsion water.

The burn time in Table 2 has been expressed as the total burn time from ignition to the point where less than 1 m^2 of the remaining slick was covered in flames. The burn rates and efficiencies given in the table are calculated based on the initial volume of oil, not emulsion. The overall burn rate was estimated as follows:

[(initial oil volume - volume residue) / (initial slick area)] / burn time

Table 2. Summary of burning of oil in ice experiments

Exp No.	Oil	Vol. (L)	Slick thickness (mm)	Ice Cover (%)	Wind speed (m/s)	Burn time (min)	Burn efficiency (%)	Burn rate (mm/min)
C1	fresh	8 000	56	20	0 - 2	14	99	2.1
C4	fresh over 50% w/o emulsion	4 000 + 5 700	68	50	1 - 3	27	99	1.8
C5	20% w/o emulsion	2 700	30	50	8 - 11	30	95	1.0

Prior to the first large scale burn, a pre-test was conducted with 200 L of fresh crude oil to assist in determining the position of the instrumented tower (see Figure 4). The oil was pumped into the basin and allowed to spread between and over the slush ice and small floes. The total oiled area was approximately 9 m^2, but because of the slush ice, snow and small floes, it was difficult to estimate the slick thickness. Some of the oil was absorbed by the snow and slush ice in some places, while in other places, un-oiled ice was present within the slick. One minute following ignition, the flames had spread over an area of approximately 3 m^2. Very little spreading of the burning slick occurred during the first few minutes of the burn. After 5 minutes the entire slick area, approximately 12 m^2 was aflame. Some spreading of the burning slick was observed, although this occurred very slowly. The fire remained fairly contained in the slush ice, spreading to a maximum area of 16 m^2. The burn lasted almost 14 minutes.

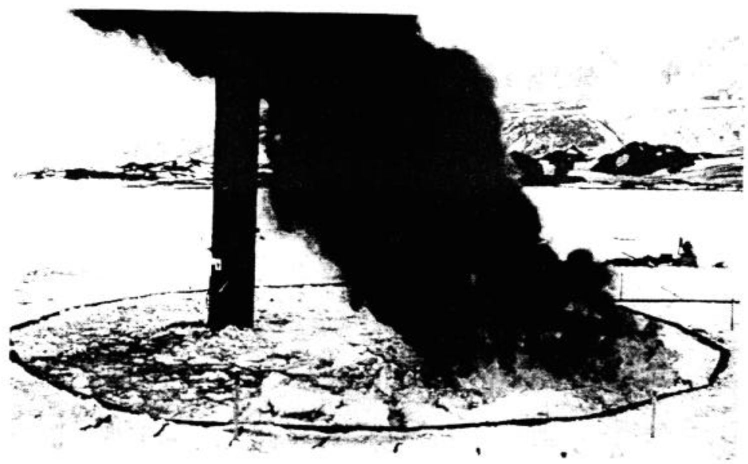

Figure 4. Pre-test burn with 200 L of fresh Statfjord crude oil in slush ice.

The first large scale burn, experiment C1, was carried with 8 m^3 of fresh oil in slush ice. Because of the large oil volume used in this experiment, much of the slush ice and snow was cover by the slick. With an ice or slush coverage of approximately 20%, the initial slick thickness was estimated to be 56 mm. The entire slick area was ignited in approximately one minute. Approximately one half drum (100 L) of residue was collected after this burn and the oil removal efficiency was estimated to be 99%.

A mixture of fresh oil and a 50% w/o emulsion was burned in experiment C4. The fresh oil was added to the emulsion slick. The total slick thickness was 68 mm, contained in an area with ice coverage of approximately 50%. The entire slick area was ignited in just over one minute. This mixture of fresh and emulsified oil burned, with an efficiency of approximately 98%.

In experiment C5, a 20% water-in-oil emulsion made from 18% evaporated Statfjord crude oil was burned in a simulated marginal ice zone. This emulsion was chosen to simulate the oil conditions encountered during the MIZ-93 experiment (Sørstrøm et al. 1994). This emulsion burned with a high efficiency, approximately 95%. The burn rate, 1.0 m/s, was considerably lower than that recorded during experiments C1 and C4. This was likely due to the high winds which prevailed during this experiment (8 to 11 m/s) causing the slick and some of the ice to be herded against the downwind end of the basin. The slick, confined to a smaller area, therefore burned for a longer period of time, and presumably to a greater degree of efficiency that it might have without the wind herding effect. This effect has been reported in a number of experimental burns (Buist et al. 1994).

Flame spreading. Figure 5 gives the layout of the smaller basins in relation to the large basin and describes the oil used in each basin for each experiment. Also indicated in this diagram are those basins in which the oil was ignited and burned during each experiment. During experiment C1, the basins contained a 10 mm slick of either fresh, 25% evaporated/50% w/o emulsion or 25% evaporated/65% w/o emulsion of Statfjord crude. The oil and emulsions in none of the small basins ignited during the burn. The wind speed during this experiment was low, ranging from 0 to 1 m/s, thus during most of the burn there was very little flame tilt. The heat was not radiated directly over the small basins. Slightly more heat was radiated towards the downwind side of the basin, indicated by the fact that some of the wooden markers surrounding the basin had charred on the downwind side of the burn only.

During experiment C4 and C5, the total burn area were smaller than in experiment C1, because of the higher ice coverage in these experiments. Therefore, it is presumed that the total heat radiated from these burns was likely lower. However, the wind velocity was greater which caused the flames to be deflected directly over some of the small basins. The flame angles were estimated to be between 30 and 35° from horizontal during experiment C4. This caused the oil in some of these basins to ignite and burn. In experiment C4, two basins, one with 25% evaporated oil and the other with a 50% water-in-oil emulsion had ignited and burned with a very high efficiency (over 95%). These basins were located 1.5 m downwind from the main basin. In experiment C5, during which wind velocities were even higher, oil in four of the basins had ignited, including two which were further away from the burn (3.5 m). These results indicate that the wind direction, and more importantly the deflection of the flames due to wind have an impact on flame spreading.

Thermal environment in contained oil slick fires. The temperatures recorded during this experiment are shown in Figure 6. The temperature field in experiment C1 is characterized by large fluctuations. Some of the fluctuations are caused by turbulent eddies of the fire plume, which after stabilizing over the entire pool area started a cyclic production of large fire balls. The frequency of these fire balls was in the order of 4 to 6 seconds. In addition to these temperature fluctuations, there also appeared to be fluctuations in the fire intensity at a frequency in the order of 20 to 30 seconds. The measured flame/smoke temperatures varied from 400 to 1370 °C, or likely higher, as 1370 °C was the maximum range for the thermocouples used in these experiments. The higher temperatures were measured 3.3 m above the sea surface, towards the centre of the pool. At the same height, but towards the edges of the fire plume, temperatures varied between 400 and 1300 °C.

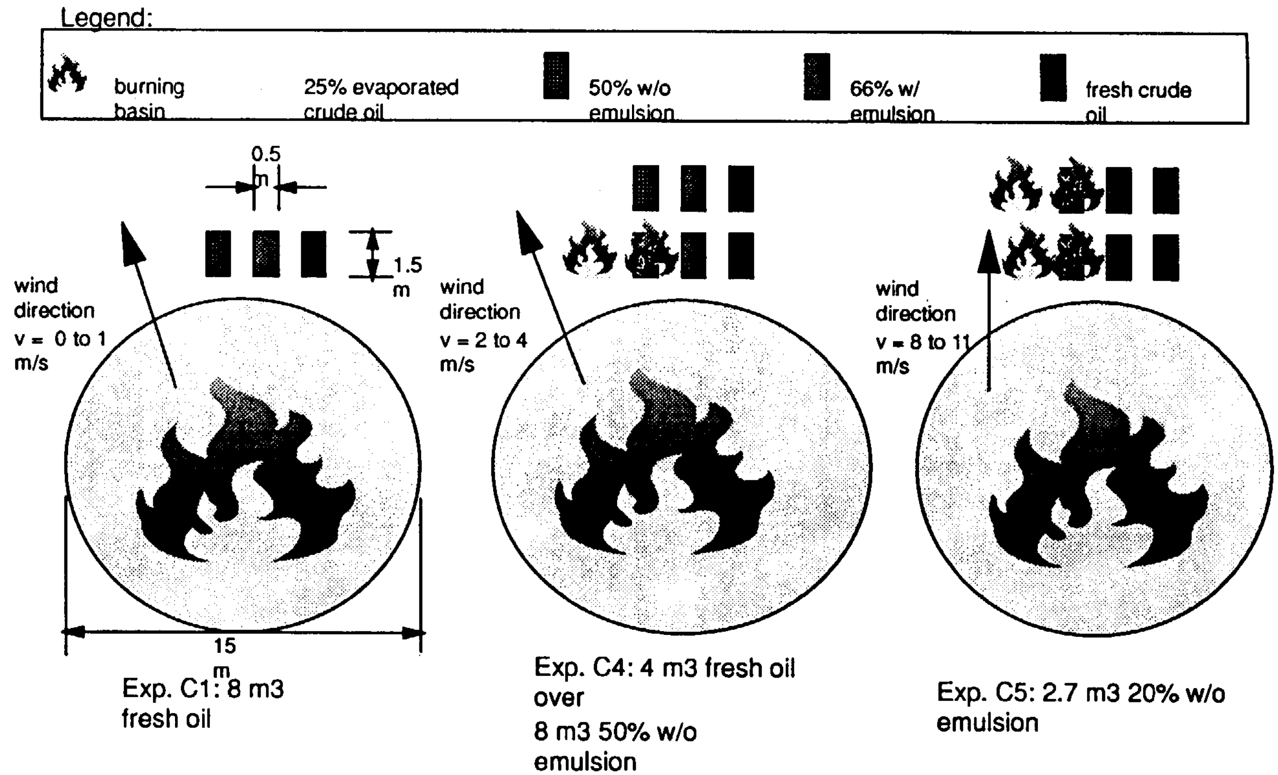

Figure 5. Layout of the smaller basins in relation to the large basin, describing the oil used in each basin for each experiment. Also indicated are those basins in which the oil was ignited and burned during each experiment.

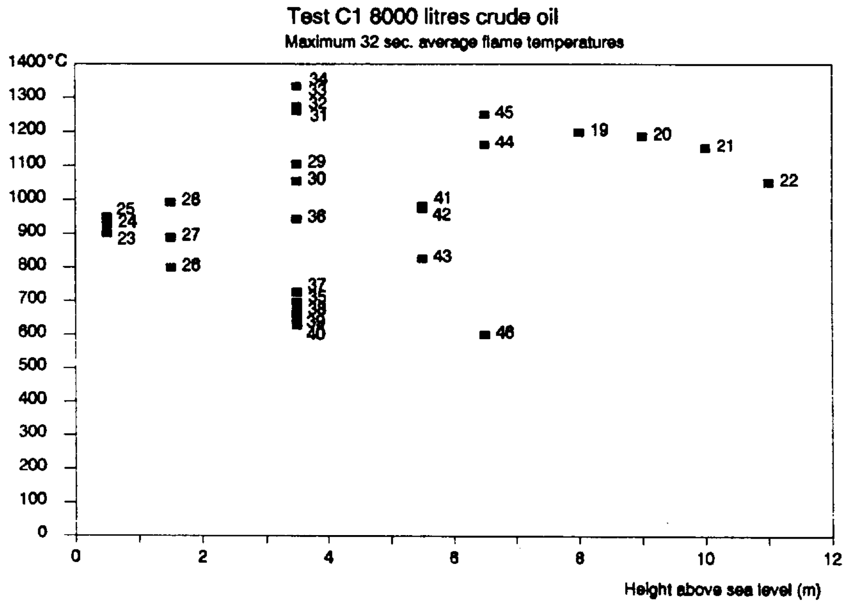

Figure 6. Maximum measured 32 seconds time average flame temperature during experiment C1. The numbers refer to thermocouple position in Figure 2.

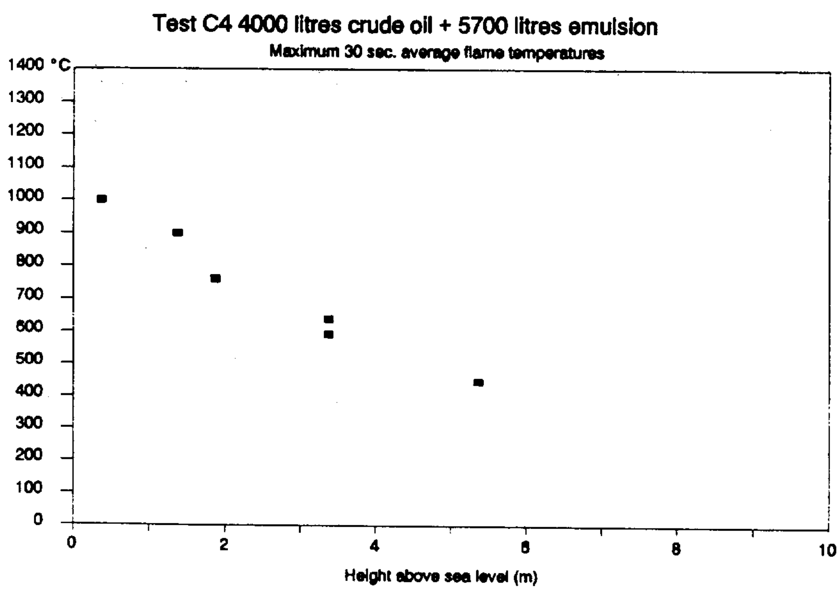

Figure 7. Maximum measured 30 second average temperature during experiment C4.

In the wake zone behind the tower, relatively low temperatures were recorded, in the order of 200°C. These readings indicate that no flames exist in this region, but rather that the thermocouples are receiving radiative heat flux from the fire plume at this point. The temperature field in this experiment C4 (see Figure 7) also exhibited some fluctuations, but they were not as pronounced as those observed in experiment C1 carried out under calmer wind conditions. The burning intensity also appeared more constant in C4 than during C1. The maximum measured flame temperatures were in the order of 1000°C at 1 m above sea level. However, the tower was positioned in the zone of the fire plume where the fire was not fully developed.

The heat flux densities measured by water cooled total heat flux meters mounted flush with the surface of the steel tower do not correspond to the high temperatures measured in the immediate vicinity. The heat flux densities also fluctuated with time and space, and the heat flux experienced by the steel tower itself corresponded with the spot measurements. The maximum values of heat flux densities measured in the 15 m diameter contained pool fire were measured 6.8 m above the sea surface. The peak measured heat flux densities to a cooled object within the flames were 400 kW/m^2, with a maximum 32 second average of 220-230 kW/m^2. The 32 second average heat flux densities varied substantially, from 130 kW/m^2 at a level of 1.8 m to 190 kW/m^2 at a level of 4.3 m.

CONCLUSIONS

The experiments have shown that high burn efficiencies can be obtained when burning fresh oil and emulsions contained in broken ice. Fresh oil and a mixture of fresh oil and a 50% w/o emulsion burned with efficiencies of over 99%. A 20% w/o emulsion burn with an efficiency of 95% in a basin with 50% broken ice coverage.

Flame spreading in broken ice conditions was observed mainly in the downwind direction. Some spreading occurred sideways and upwind between interconnected slick areas. Flame spreading from one burning oil pool to another separate oil pool was dependent on the wind speed and direction. Spreading occurred when the pool was located directly downwind from the burn and winds were sufficiently high to deflect the flames far enough such that the pool was directly exposed to radiant heat. Small pools of 25% evaporated oil and 50% w/o emulsions burns to high efficiency when ignited in this way. Deflection was shown to be more important in flame spreading than the size of the fire. Larger fires with no flame tilt were less effective in flame spreading than smaller fires with flame tilt.

Temperatures measured in the flames were higher than previously measured in pool fires. Heat fluxes were also somewhat higher than expect or normally used in structural analysis.

ACKNOWLEDGEMENTS

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