Fire on the Sea Surface, Ignitability and Sustainability under Various Environmental Conditions

K. OPSTAD, SINTEF Civil and Environmental Engineering, 7465 Trondheim
C. GUÉNETTE[1], SINTEF Applied Chemistry, 7465 Trondheim

ABSTRACT

A series of laboratory tests were carried out to determine the potential for ignition and sustained burning of spilled oil at sea resulting from ignition sources on an offshore platform. The variables considered were; ignition source type and strength, oil types, spilled oil behaviour and environmental conditions. This study assessed the effects of variations in fuel properties, oil slick thickness and wind conditions. The current state of knowledge was assessed through various phases of the project. The conclusion and assessment of the ignitability of crude oil spilled at sea are considered in light of these laboratory experiments, as well as of finding from previous field and laboratory experiments in the area of oil spill response

KEYWORDS: Fire, Experimental, Fire at Sea, Oil spill, Ignition, Sustained Burning

INTRODUCTION

In general, fire at sea may have severe consequences on the safety of an offshore installation. Consequences are related to heat load on structures, smoke impact on the installation and limiting access for evacuation and rescue operations. In the early nineties, fires on the sea surface have been treated in the same way as topside fires (Webb 1993). Thereafter experience gained in the filed of "in situ burning", the deliberate ignition and burning of oil at sea as an oil spill response option has also been considered. The deliberate ignition of oil for environmental protection, normally takes place after some weathering of the oil has occurred, which may lead to misinterpretation when these results are used for safety purposes. Oil released onto the sea surface undergoes a number of physical process collectively known as weathering, of which the most important with respect to burning and evaporation, emulsification and spreading. Recently, several research programmes have been undertaken to understand and quantify the consequences of fires at sea. This evaluation, in which both the heat transfer and threshold ignition are reported, is based on the conclusions from a literature review and results of experimental series reported by Guénette *et al.* 1997. The project was sponsored by BP Group Research and Engineering (UK), Elf Petroleum Norge A/S (Norway), Health & Safety Executive (UK), Norsk Hydro A/S (Norway), Saga Petroleum A/S (Norway) and Statoil (Norway).

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[1] Presently at International Tanker Owners Pollution Federation, London, UK

PRINCIPLES OF IGNITION AND SUSTAINED BURNING

The principles of igniting spilled oil films on water and the factors that influence the sustainability of the burn have been described (Allen, 1991) and reviewed in several published studies (Thompson *et al.* 1979, Evans *et al.* 1993, Putorti *et al.* 1994, Buist *et al.* 1994, Walavalkar and Kulkarni, 1996). Most of this research has been carried out in the context of in situ burning and oil spill clean-up.

In general, combustibility and ignitability of crude oil on sea surface is significantly affect by both the heat losses to water and weathering of the lightest fraction of the oil as function of environmental parameters and time.

Ignition

Ignition of an oil slick occurs when the surface temperature of the slick is raised to its flash point: the point where the hydrocarbons are vaporised in sufficient concentrations to support combustion. In order for flame spread and sustained burning to occur, the liquid surface temperature just ahead of the burning region must reach its fire point, which is usually several degrees higher than the flash point. This is the temperature at which the rate of vaporisation is equal to or greater than the rate of combustion. Therefore for successful ignition of a slick to occur, the ignition source must be capable of raising the slick surface to its fire point.

Burning is initiated by ignition of flammable vapour above the oil film by the application of a flame or spark. The flammable vapour must be present in sufficient concentration for ignition to occur. Ignition of oil spilled from a damaged installation could occur in several ways;

<u>Low energy ignition</u>
Flammable vapour may be produced from the crude oil by evaporation at ambient temperature. In this case the ignition source can be of relatively low energy such as a spark; its sole purpose is to ignite a flammable vapour already present.

Evaporation of flammable components from crude oil at the prevailing sea temperature provides the fuel for low energy ignition. When crude oil is spilled on the sea the most volatile and flammable components will evaporate and form a vapour 'cloud' above the oil slick which will diffuse into the air and be dispersed by the wind. The critical factor for low energy ignition is that the flammable vapour concentration should be maintained above a minimum level (the lean limit of flammability) when the ignition source is present.

<u>Higher energy ignition</u>
If the concentration of flammable vapour above the oil is too low to support ignition it can be supplemented by the use of a higher energy ignition source (energy sources to support gasification of oil, like burning objects close to oil surface). Ignition of oil that has been depleted of the most volatile and flammable components can be achieved by providing heat from an ignition source. This will locally raise the oil temperature and enable heavier oil components to evaporate and enter the vapour phase. Once in the vapour phase, these components can be ignited by the ignition source, provided they are present in sufficient concentration.

Heat Absorption in Oil and Loss to Underlying Water

Transfer of heat to the oil layer will be controlled by the intensity, proximity and duration of exposure of the ignition source. The amount of heat absorbed by the oil film, and therefore the increase in temperature of the oil in the film, depends on the heat capacity of the oil film and the proportion of heat transmitted, or lost, to the underlying water. The amount of heat absorbed is controlled by the oil film thickness; thin oil films will lose too much heat to the water for sufficient evaporation of the oil to occur and ignition will not be possible. The precise minimum thickness for successful ignition varies with oil type and composition. Crude oils that contain a high proportion of volatile and flammable components will be more easily ignited at a lower film thickness than heavier oils. Early work on burning of uncontained oil slicks (Buist and Twardus, 1985) showed that burning could be very effective, provided that ignition took place before the volatile components had evaporated and before the slick had spread to below a minimum thickness of about 0.8 mm for fresh crude oil. Minimum oil film thickness of 1 - 3 mm (Allen, 1991) have been suggested for relatively fresh crude oils, increasing to 10 mm or more for heavy bunker fuel oils or emulsions. The minimum oil thickness for ignition probably increases with wind speed (Gregory *et al.* 1996).

Sustained Burning

The radiated heat from flames of burning oil will generate flammable vapour and burning may become self sustaining while fuel is available. Burning in any particular area is sustained by heat of the flames liberating more vaporised fuel from the oil which is then ignited and burns, thus liberating further heat. The oil that is burning will rapidly become depleted in the lightest components (Evans *et al.* 1986 and 1988). The surface temperature of the crude oil in a burning oil slick has been estimated to be around 300°C (Evans *et al.* 1993). Oil components that can be vaporised at this temperature are the fuel for the initial stages of sustained burning. Components that boil at up to 350 °C have been identified as the important oil components for sustained burning (Buist *et al.* 1994). They must be present in the oil and the ease with which these components can be vaporised depends on the composition of the oil (Evans *et al.* 1988). All crude oils will contain enough of these components to act as the fuel for sustained burning. The major obstacle to burning of spilled oil, as an oil spill response technique, is the formation of water-in-oil emulsions (Bech *et al.* 1993 and Guénette *et al.* 1995). Burning of thin oil films leads to heat being transferred to the underlying water. This can cause boiling (or 'boil over') of the water (Evans, 1988) and this vigorous boiling can enhance the combustion process by ejecting droplets of oil into the flame and reducing smoke production.

Flame Spreading

The flame of burning vapour, established above the oil film, will radiate heat to areas of the slick not originally heated by the ignition source. Most of this thermal radiation transmitted to the oil film on the water comes from the lowest part of the flame and can be blocked by cold smoke (Koseki, 1993). Heat will raise the temperature of the oil and the

generation of flammable vapour will occur if the temperature can be elevated sufficiently. The major factors controlling flame spread are the radiant heat intensity produced by the flames and the ability of the oil film to absorb this heat. The heat content, thickness and presence of emulsion in the oil film are significant factors (Evans *et al.* 1993 and Walavalkar and Kulkarni, 1996). The radiant heat will raise the temperature of the surrounding areas of the slick that are not yet on fire. This heating will liberate volatile components which will then ignite. For materials that are difficult to ignite, such as emulsions, flames need to be present over a relatively large area to promote further flame spread and subsequent combustion, compared to easily ignited materials (Bech *et al.* 1993). A centrally located fire should spread outwards to increase the burning area. In practice, wind influences this process by tilting the plume and causing more intense radiation downwind and flame spreading along wind axis (Guénette *et al.* 1995).

Extinction

Extinction of a burning slick occurs when a minimum slick thickness is reached (approx. 0,8mm) which can no longer support burning. The burning process stops when the fuel is exhausted or cannot be liberated from the oil residue by the radiant heat. Disruption of the flame spreading process will lead to a greater proportion of burn residue remaining after combustion (Buist *et al.* 1996).

Effect of Environmental Conditions

The impact of environmental conditions on the state of the oil has been studied and is reported in Bech *et al.* 1991, Bech *et al.* 1993, Cabioc'h and Garo 1993, Energetex Engineering 1977, Farmwald and Nelson 1982, Guénette *et al.* 1994, Hossain and McKay 1981, Putorti 1994, Smith and Diaz, 1985. Generally, it has been found that wind speed can increase the rate of ignition and flame spreading. The wind herding effect, whereby oil is herded against a barrier (e.g. ice, tanker, platform leg, floating object) can increase the duration of the burn by maintaining the slick at a thickness capable of supporting burning for a longer period of time than if it were free floating. However, excessive winds can also make ignition and sustained burning difficult. This effect is dependent on the oil type and conditions. The presence of waves can prevent the ignition of marginally ignitable oils and stable emulsions, due to the temporary thinning of the slick at the crest of the swell.

EXPERIMENTAL SERIES AND SET-UP

The mechanisms controlling the ignition of an oil slick on the sea surface are governed primarily by the rate of evaporation of ignitable components from the oil slick, dilution of the fuel vapour above the slick surface and the strength of the ignition source. If an oil slick is ignited locally, the possibility of flame spread and sustained fire is controlled by the conditions of the oil slick in the vicinity of the ignition area, which are also predominantly influenced by the environmental conditions. A series of meso-scaled tests was carried out at SINTEF (Norwegian Fire Research Laboratory) to investigate conditions

required for ignition and sustained burning of various oils (Guénette *et al.* 1997). These test burns were carried out in a specially designed basin placed inside a wind tunnel.

The environmental conditions varied and monitored in these tests were the air flow velocity and sea/slick temperature. The effect of size of the ignition sources (the heat exposure) and, the effect of slick thickness was also investigated.

Test Rig and Set-up

The test rig consisted of a wind tunnel containing the test tank (Figure 1). The basin containing the pool of oil was build into the floor, such that the fuel surface was almost at the same level as the floor. In all tests, the fuel slick was placed on top of at least 150 mm of water. Oil, water and air temperature could not be maintained constant throughout the experimental series as these were influenced by the weather conditions. That includes the slick area as well, which was reduced due to the wind herding effect. At low wind velocities, the slick area remained constant; however, at higher wind speed, the oil on the water surface was herded to the downwind end of the basin.
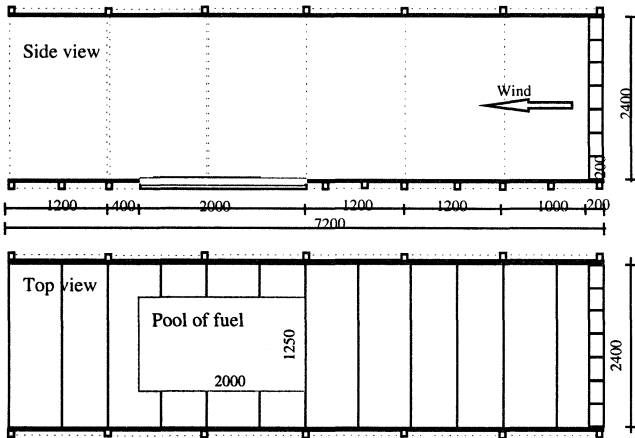

FIGURE 1   *General arrangement of test rig*

The wind tunnel was of square section (2.4 m high and 2.4 m wide) and 7.2 m long lined with plasterboard. The air intake to the wind tunnel was positioned by the large doors of the test hall so that outside air could be admitted at one end, and drawn in by the air flow created by the exhaust fans of the test hall. Fresh outside air was therefore drawn in without re-circulation and the exhaust air (containing the smoke from the burns) was passed through filters and released outside. The velocity of the air passing through the wind tunnel was controlled by adjusting the speed of the exhaust fans. The cross wind component of the air flow into the wind tunnel was removed by drawing the air through a grid of vertical and horizontal wooden slats, 0.1 m wide with 0.2 m by 0.2 m spacing in both axes.
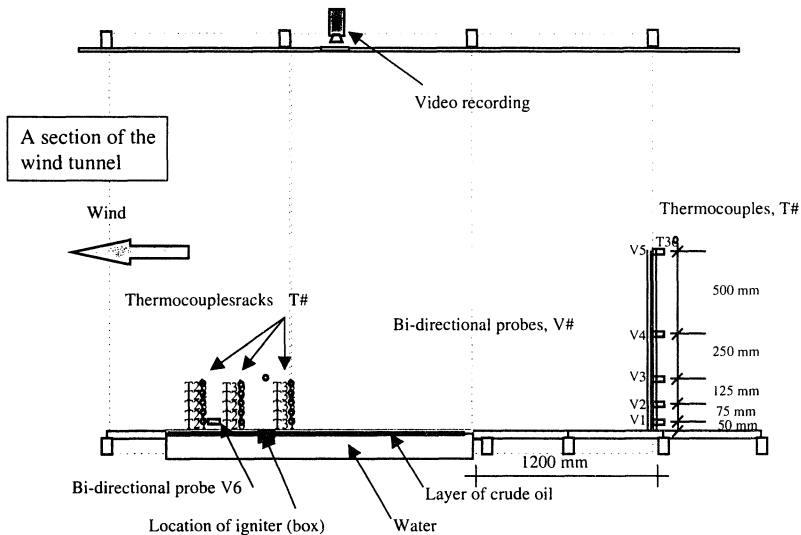
FIGURE 2 S*ide view normal to the centre line of a section of the wind tunnel. All instrumentation placed on the centre lined is shown, except instrumentation of the pool itself. Copper plates are placed above the oil surface at the same location as three thermocouple racks. Heat flux to surface is derived from the temperature readings of these copper plates.*

Instrumentation

The location of the main measurement devices is shown in Figure 2 below. The instrumentation was used to record the following:

- Air and oil/water temperature, measured using K type thermocouple 0.8 mm wired and K type mounted on a copper plate.
- Flow rate of air by velocity in single points, measured using bi-directional probes.
- Heat flux was measured using two heat flux transducers type Gardon gauge water cooled radiometers. The heat flux density within the pool was measured by use of temperature readings of copper plates. The heat flux density was derived from the combination of heat radiation term from above and one heat convective term to consider engulfment of flames.
- Video recording from a top view and a side view was used for measuring the flame spread rate and time to ignition.

Oil Types Used in the Experiments

The four test oils used in these tests can be classified as follows:

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Sleipner condensate	condensate
Statfjord crude (fresh)	light crude
Troll crude and Statfjord crude (evaporated)[2]	heavier crude

Properties of the oil used in the experiments are probably best described by the distillation curves. The boiling point or distillation curves for the three oils, taken from the crude oil assays, are presented in Figure 3.
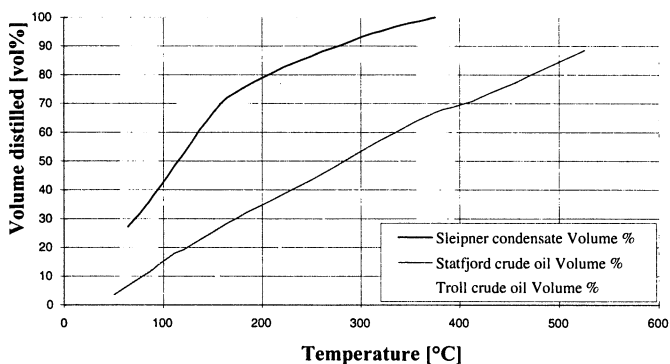

FIGURE 3   *The distillation curves for the test oils. The initial properties of the test oil are described by the distillation curves. Oils with the highest mass loss as function of temperature are more volatile than those with lower mass loss.*

The significance of the composition, and therefore the chemical and physical properties, on ignitability and burning behaviour is discussed in Guénette *et al.* 1997. The volume of the oil that distils at 150°C (broadly the gasoline fraction and lower) is a guide to the amount of oil components that will readily evaporate at much lower temperatures (around 10°C) in about 30 minutes to 1 hour.

The Ignition Source

The main ignition sources used consisted of small pools of the test oil contained at the surface of the slick in a square metal box, open at the top and bottom. The heat input from the ignition source was varied by varying the surface area of this small pool. Three boxes were built for this purpose, with surface areas of 2, 8 and 18 cm². The oil in the box was ignited using a flame from a propane torch. The flame from the propane torch was itself used as an ignition source for oil slicks easily ignited with the smallest ignition box.

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[2] Statfjord crude (evaporated) artificially evaporated by bubbling air through the oil until 11,3% of the oil was lost by evaporation.

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The Meso-Scaled Basin Test Matrix

The test parameters are summarised in Table 1. A total of 22 experiments were carried out using a combination of these test parameters. A total of 31 tests were carried out in the test programme (Guénette et al. 1987). The results from which were expected to contribute to the overall understanding of the ignitability of crude oil on water.

TABLE 1 *Test parameters for basin tests*

Oil type	Condensate	Light crude oil	Heavier crude oil
slick thickness (mm)	15, 20	1, 15, 20	1, 15, 20
air flow velocity (m/s)	10, 15	0, 5, 10, 15	0, 5, 10, 15
igniter size (box-cm^2)	torch	torch, 2, 8, 18	torch, 2, 8, 18

RESULTS

The Sleipner condensate and fresh Statfjord crude proved to be extremely easy to ignite. Under all environmental conditions tested, these oils ignited in less than one second. The evaporated Statfjord and Troll crudes were also easy to ignite when the air flow velocity was 10 m/s or less and the slick thickness was at least 15 mm. The evaporated Statfjord and fresh Troll did not ignite at air flow velocities of 15 m/s.

In the cases where the slicks did not ignite (evaporated Statfjord and Troll at 15 m/s), flames were present on the slick surface downwind from the ignition sources only as long as the flame from the propane torch was in contact with the slick (ignition box).

Effect of Slick Thickness

The effect of slick thickness on the time to ignition was studied with fresh Statfjord and Troll crudes. (One experiment was done with Statfjord using the smallest ignition source, and two experiments were carried out with Troll using the smallest and the largest ignition sources.) Two tests were carried out with each oil, at a film thickness of 1 and 20 mm, using the smallest ignition sources. The air flow velocity and air temperature were approximately the same during all four tests, ranging from 0,5 to 0,9 m/s and 6 to 9,4 °C respectively. The ignition time for Statfjord did not appear to be affected by slick thickness, whereas a marked increase in time was required to ignite a thin slick of Troll crude. The Statfjord crude slick was ignited in less than one second with a match as the ignition source (the match was ignited and dropped from about 1 m above surface). Ignition of the Troll crude did not occur until after 15 seconds.

The effect of the size of this ignition source on the ignitability of the tested oils is not conclusively evident from the results obtained from the basin tests. The heat release from the ignition sources selected for the test programme were all greater than the limiting ignition source required to ignite the condensate and fresh Statfjord crude oil in all air flow conditions tested. The heat exposure to the surface for Statfjord crude, within the first second of flame exposure as measured is presented as the solid line in Figure 4. This exposure represents the heat transfer from the igniter box to the slick surface, and presumably represents significantly more heat transfer than the propane flame used to ignite the box. It is evident from this figure that the ignition sources did not provide constant exposure at various air flow rates. As shown in this figure, the exposure from the igniter boxes are highest in the air flow velocity range of 5 to 10 m/s. This is due to the flame deflection caused by the air flow rate, thereby increasing the heat exposure to the slick. The heat transfer to surface from ignition sources is one of the keys for flame spread of heavier crude oil, where a thermal flame spread approach may apply.

Also indicated on Figure 4 are the 'ignition risk areas', in other words the conditions (related to the air flow velocity and heat exposure) under a risk of ignition of the Statfjord crude oil is presented.
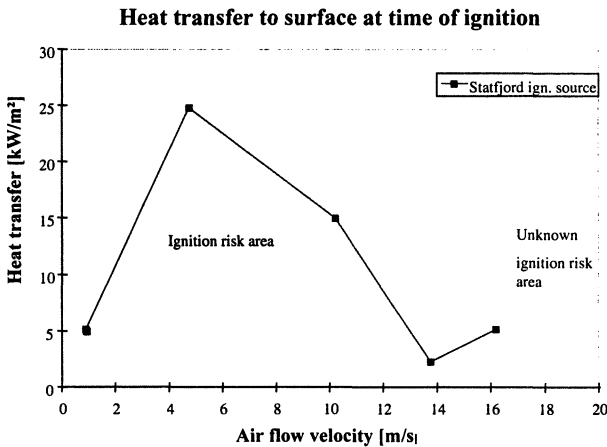
Heat transfer to surface at time of ignition

FIGURE 4   *Statfjord fresh crude oil ignitability as function of air flow velocity. The slick thickness is more than 15 mm and the oil temperature is approximately 10 °C. The shaded area indicates risk for ignition from any open flame contacting the surface. The solid line gives the measured heat transfer, at the downwind edge of the ignition box to the oil surface within the first seconds after the pilot igniter is positioned. (16 m/s air flow velocity is the highest investigated)*

The basin tests indicated that for fresh Statfjord crude, an open flame at the surface is sufficient to ignite the oil and cause downwind and sidewind flame spread in winds of at

least 15 m/s. No preheating of the surface is needed and therefore the risk area of ignition shown in Figure 4 is filled in from zero heat exposure on upwards. The same can be assumed for the Sleipner condensate. Air flow velocity of 10 m/s or less, the conditions required for the ignition of Troll were similar to those for Statfjord crude, although the flame spreading rate was considerably lower. The risk of ignition at higher air flow rates than 16 m/s has not been investigated experimentally.

DISCUSSION

There is a high potential for accidental ignition of condensate and light crude oil spilled at sea over a very wide range of wind conditions. The potential for accidental ignition of heavier crude oils such as Troll crude is lower, but still significant in some conditions.

The wind effect of diluting the volatile gases does not apply for "fresh" light oils in winds up to 25 m/s which is equivalents to about 50 knots. According to (Opstad et al. 1998), high breaking waves and foam covering most of the sea surface is expected under these wind conditions. The evaporation will probably not be significantly affected by "sea foam/mist" and by braking waves. Therefore the risk of ignition is presumed to exist under these conditions.

CONCLUSIONS

The difference in initial ignitability and subsequent burning of crude oil at sea appears to be due to differences in the flammable vapour concentration created above the spilled oil. The vapour concentration above a slick is a function of:

- Oil composition (the proportion of the most volatile and flammable components with boiling points below 150 °C)
- The prevailing temperature which controls the rate of evaporation of the volatile and flammable components

Wind aided evaporation, due to dilution of fuel vapour, influences the resulting vapour concentration gradient above the surface. Ignitable concentrations of flammable vapour persisted in the boundary layer even at high air flow. An increasing air flow velocity does not cause dilution of the flammable vapour concentration above the surface initially after a crude release.

An ignitable layer will be formed and will therefore also be possible to ignite. However, the burning may obviously be weak. The main wind effects on ignition are:

- Cooling the surfaces and the ignition source
- Increasing turbulence and changing the chemical reaction rate. If the minimum extinction time scale is exceeded, ignition and flame spread will be impossible
- Weathering the oil and evaporating the light fractions

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