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FIELD EXPERIMENT TO VALIDATE HERDER AND IN-SITU BURNING USE IN OPEN WATER.

ABSTRACT

A series of experiments involving herders and in-situ burning (ISB) were conducted at sea on 14th – 15th June 2016, at the Frigg Field in the North Sea (59o52'48''N; 02o03'59''E). The primary objective was to demonstrate, at near-full scale, the use of herders followed by ISB in open water conditions and validate the findings of an earlier field study. The experiments demonstrated that oil slicks in calmer open water can be contracted by herder and ignited by using small boats to deploy ignitors. However, operating from the sea surface requires aerial guidance and the greatest difficulty in this trial was in observing and locating the areas of thick oil. The limitations of real-time aerial guidance directly to the boat crews from drones and remote sensing aircraft resulted in difficulties in applying herder effectively for one of the experiments and igniters for two of the experiments. The lack of real-time guidance also contributed to the splitting of oil slicks by MOB boats, so only parts of the thick oil (> 1 mm) were ignited. Each of the three slicks was allowed to float on the sea surface for approximately 50 minutes before ignition was attempted. Under the calm weather conditions, spreading was limited and all slicks still had areas with thick oil (> 1 mm) after that time. The two slicks released for herding had spread out to an average thickness of just over 1 mm before herder was applied. Herding increased the average oil thickness to 3.7 mm (HISB 4.1) and 2.6 mm (HISB 4.3). Under the very calm sea conditions, the spreading of the more compact reference (HISB 4.2) slick was more limited than that of the other two slicks and the oil ignited even though the oil had not been herded. If the reference slick had been released in the same way as HISB 4.1 or under slightly rougher weather conditions as HISB 4.3, the oil film thickness could have dropped to below 1 mm prior to herding, given a few hours on the sea surface. Previous studies indicate that ignition of slicks below this thickness threshold, without herding first, would not likely be successful. Future use of herder should utilize a real-time video link from aerial overflight platforms to vessels applying herder on the surface to permit accurate application of herder and target ignition to the thicker portions of a slick. In spite of the shortcoming and practical challenges the experiments were successful in the narrow weather window given (< 5 m/s wind) and verified the successful use of herders in open water conditions.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Three experimental releases of Grane Blend crude oil to sea were performed at the Frigg field in the North Sea in June 2016, to verify the use of herders and *in-situ* burning (ISB) in open water conditions. Two slicks were herded before ignition, while the third "reference" slick was not treated with herder. The test oil was Grane Blend crude oil and the herder used was ThickSlick 6535, supplied by DESMI. A fourth experiment was performed the next day, in breaking wave conditions, with the release of 5 litres of herder alone to study the potential dampening of wind driven white caps.

The release conditions and the weather conditions were slightly different for the three oil releases:

- Slick 1 (HISB 4.1): 6 m^3 of oil was released over a distance of 50 to 80 metres as a long narrow slick under very calm conditions (3-4 m/s wind; no breaking waves). The majority (approximately 80 %) of the thick oil area in this slick was herded.
- Slick 2 (HISB 4.2; "reference"): 6 m^3 of oil was released as a point release over a distance of 50 metres under very calm conditions (3-4 m/s wind; no breaking waves). This gave a more compact area of thick oil compared to slick 1. This slick was not treated with herder.
- Slick 3 (HISB 4.3): 4 m^3 of oil was released as a point release under slightly rougher conditions (5 m/s wind; occasional breaking waves). This started as a compact area of thick oil. As the slick drifted with the wind, it spread out to form a larger slick with thin and thick oil areas. Parts of this slick were herded.

For slicks 1 and 3 application of herder started approximately 30 min after release of oil. For all slicks the first ignition started approximately 50 min after finalization of the oil release.

Two different approaches were used to evaluate the results from these experiments:

1. The main approach was to analyse the amount of oil (as an area or derived volume) that was present as oil thicker than 1 mm (regarded as a minimum thickness for successful ignition). The approach includes analysis of a large amount of pictures and videos, combined with a few oil thickness measurements, and depends upon:
   i. How much oil was released and how the oil spread out on the sea surface into areas of thick and thin oil.
   ii. How much of the thick oil was then surrounded by herder.
   iii. What happened to the area of the thick oil after herding.
   iv. How much oil (area, thickness and amount) was available for, or exposed to, ignition.

   This approach is referred to as "Analysis of Spreading and Herding for Burning" (ASHB).

2. The other approach, known as the Integrated Time-Area (ITA) approach, is a method of estimating burn effectiveness and determines the percentage of originally spilled oil that was burned. The Integrated Time-Area (ITA) approach is described in appendix G. The flame area is estimated, integrated over the duration of the burn(s) and is multiplied by an assumed burn rate of 3 mm/min. The amount of oil estimated to have been burned is then calculated. The ITA approach does not explicitly refer to the influence of a herder being used.

Both approaches includes a high degree of uncertainty and the results presented should be regarded as best estimations. Another complicating factor was that for two of the experiments (HISB 4.2 and 4.3) MOB (Man Over Board) boats moved through and split up the oil slicks due to absence of the real-time aerial guidance. This resulted in portions of each slick remaining un-herded and/or un-ignited.

The first test with herders (HISB 4.1) was on oil that had spread to a thickness of between 1.1 and 1.6 mm before herder application. Approximately 80 % of the available thick oil area was herded and the thickness of the herded oil increased to between 3.0 to 4.6 mm. It was estimated that 75 % (range of 55 % to 95 %) of the herded oil was subjected to ignition and burning, which equals approximately 3.5 m^3 of oil (Table 9.1).

The second test with herders (HISB 4.3) was conducted during higher wind speed conditions. The thick oil area had spread to a thickness of between 1.0 to 1.3 mm before herder application. Due to splitting of the slick by MOB boats during herder application, approximately 40 % of the available thick oil was herded and the thickness increased to between 2.1 and 3.2 mm. With further splitting of the herded slick it was estimated that only 50 % (range of 40 % to 65 %) of the herded oil was subjected to ignition and burning. The estimated volume of oil subjected to burning was 0.8 m^3, keeping in mind that only 4 m^3 oil was released in this experiment as opposed to 6 m^3 in each of the two other releases (Table 9.1).

In the test without use of herders (HISB 4.2; "reference"), oil had slightly spread but remained at a thickness of 2.4 to 2.9 mm prior to ignition (within approximately 1 hour). This thickness is well above what is regarded as minimum for ignition. Also, in this experiment the slick was divided into several parts by MOB boats making it difficult to ignite all the parts of the slick. Therefore, only 25 % (range of 20 % to 30 %) of the available thick oil was subjected to ignition and burning. The estimated volume of oil subjected to burning was 1.4 m^3 (Table 9.1).

The limited time of approximately 1 hr allowed before ignition was a prerequisite for doing the experiments as set forth in the permitted operational plan. All three slicks were released in different ways and/or weather conditions. The reference slick (HISB 4.2) was released as a point release in contrast to the HISB 4.1, which was released over a distance (larger initial spreading). HISB 4.3 was also a point release, but the weather was rougher (5 m/s wind speed) giving a higher initial oil drift/spreading. The reference slick, being discharged in a concentrated way (point release) and not being subjected to higher winds as HISB 4.3, was initially more compact with higher thickness than the other two persisting before herding/ignition. If the reference slick had been released in the same way as HISB 4.1 or under slightly rougher weather conditions as HISB 4.3, the oil film thickness could have dropped to below 1 mm prior to herding given more time on the sea surface (e.g. a few hours). Ignition of slicks below this thickness threshold without herding first would not likely be successful.

Comparison of the estimated volumes of oil subjected to burning (ignited) from the ASHB approach with estimated volume of oil burned based on the ITA approach (Table 1) shows comparable results indicating only minor differences in burn efficiency between the different experiments. By combining estimated volume of oil burned (ITA) with approximate volume of oil subjected to burning (ASHB) it is possible to calculate an estimated burn efficiency within a range, as given in Table 1.

Table 1 Comparison of estimated volumes of oil subjected to burning (ignited) from ASHB analysis with estimated volumes of oil burned based on the ITA approach, and estimated burn efficiency based on these figures.

Experiment	Approximate volume of oil subjected to burning, m^3 ASHB approach	Estimated volume of oil burned, m^3 ITA Approach	Estimated burn efficiency for the amount of oil subjected to burning*, %
HISB 4.1	3.5 (range 2.5 – 4.4)	3.4 (range 2.5 – 4.3)	57% - 98%
HISB 4.2	1.4 (range 1.1 – 1.7)	1.2 (range 0.9 – 1.5)	53% - 90%
HISB 4.3	0.8 (range 0.6 – 1.0)	0.8 (range 0.6 – 1.0)	60% - 100%

* Calculated from estimated volume burned as a percentage of approximate volume subjected to burning.

The experiments demonstrated that in open water with winds up to 5 m/s (the maximum wind speed tested) slicks can be contracted by herder and burned with burn efficiencies well over 50% and perhaps over 90%. The absence of a real-time aerial image downlink to the boat crews and resulting splitting of the slick by the MOB boats in two of the experiments, resulted in a minority of the thick oil being herded in experiment HISB 4.3 and ignition of only part of the thick oil in experiment HISB 4.2 ("reference") and herded oil in experiment HISB 4.3. These significant operational issues arose because the boat crews applying herder and igniting the slicks could not clearly see where the oil slicks were. This information had to be interpreted and then communicated with a time delay to these boats from the main vessel that had direct down links from aerial remote sensing platforms. The challenges with this communication process resulted in the MOB boats inadvertently traversing and splitting the slicks. Future use of herders with boat-based application systems should provide a real-time direct video links from aerial overflight platforms to the boat crews to maintain positional awareness relative to the slicks.

The experience of using booms for containment and recovery of burn residue proved very difficult as the residue from the asphaltenic Grane Blend crude oil was sticky, viscous and floated partly awash in the water. Even when it was possible to contain some of the burn residue, only very small amounts were recovered. Recovery of burn residues from free-floating slicks is complicated due to the extensive spreading of oil and difficulty in monitoring the burn residue. In this trial, non-ignited parts of the slicks were treated with a total of 2.2 m^3 of Dasic NS dispersant.

Smoke from the burns was sampled by a drone and analysed after the field trial. The total particle concentration (PM2.5-particles) (filter method) measured from the drone was very high (23.5 to 34.4 mg/m^3), which corresponds to estimated levels of 57 to 137 mg/m^3 when the drone was actually in the smoke plume (Norwegian Occupational Exposure Limit (OEL) =10 mg/m^3). However, these airborne readings do not reflect the particulate exposures for personnel on the water. The concentration of PM2.5 particles was low for both the MOB boat and the Coast Guard vessel during the actual burning process. At the Coast Guard vessel, the concentration of total particles was below the limit of detection when the filter method was used. Not surprisingly, in the smoke plume itself, particulate PAH components were detected at levels approaching the Norwegian OELs, but as with the particulate measurements, these airborne readings are not representative of surface exposure levels.

1 INTRODUCTION

The Herder and In-Situ Burning (HISB) project, sponsored by the International Association of Oil and Gas Producers (IOGP), Arctic Oil Spill Response Technology – Joint Industry Programme, was performed to validate the use of herding agents in conjunction with in-situ burning (ISB) as an oil removal technique in open-water conditions. The field experiment portion of the project was an integrated part of the 2016 NOFO Oil On Water field trial (OPV 2016) at the Frigg field in the North Sea, June 14^{th} – 16^{th}. Prior to the field trial SL Ross and SINTEF performed laboratory testing with use of herders on relevant test oils and SINTEF performed ecotoxicity testing of herders and herder components.

2 BACKGROUND

Herders are surfactants that have a spreading coefficient that is greater than that of oil on a water surface. Herders can be applied around oil slicks to contract the oil slick area and thus thicken the oil layer. The use of herders in oil spill response were first investigated in the 1970s. More recent research has concentrated on the potential of using herders on oil spilled in drift ice.

Small-scale laboratory experiments were completed in 2003 and 2005 (SL Ross 2004, 2005) to examine the idea of using herding agents to thicken oil slicks among drift ice for the purpose of ISB. Encouraging results prompted further mid-scale testing in 2006 and 2007 at the US Army Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, NH; at Ohmsett, the National Oil Spill Response Research & Renewable Energy Test Facility in Leonardo, NJ; and, at the Fire Training Grounds in Prudhoe Bay, AK (SL Ross 2007).

The non-proprietary hydrocarbon-based herder formulation (now called ThickSlick 6535) used in these experiments proved effective in considerably contracting oil slicks in brash and slush ice concentrations of up to 70% coverage. Herded slick thicknesses were well in excess of 3 mm, the minimum required for ignition of weathered crude oil on water. Herded slicks were ignited, and burned equally well in both light brash and light slush ice conditions at air temperatures as low as –17°C. The burn efficiencies measured for the herded slicks were only slightly less than the theoretical maximums achievable for equivalent-sized, physically-contained slicks on water.

Successful mid-scale field trials of the technique were carried out in the Barents Sea off Svalbard in the spring of 2008 as one facet of a large joint industry project on oil spill response in ice co-ordinated by SINTEF (Buist et al. 2010a). These experiments included one release of 630 L of fresh Heidrun crude onto water in a large lead. The free-drifting oil was allowed to spread for 15 minutes until it was theoretically too thin to ignite, and then herder was applied around the slick periphery from a small boat using garden sprayers. The slick contracted and thickened for approximately 10 minutes at which time the upwind end was ignited. A 9-minute long burn ensued that consumed an estimated 90% of the oil.

From 2007 to 2009 experiments were carried out in the laboratory and at CRREL comparing the effectiveness of herding agents formulated with silicone-based surfactants, herding agents formulated with second-generation fluorosurfactants, and the hydrocarbon-based herder (Buist et al 2010b). The results showed that the fluorosurfactant-based herders did not function better than the hydrocarbon-based herder; however, the new silicone surfactant formulations successfully outperformed the hydrocarbon-based herder. More recently, experiments were conducted to determine if herding agents could: a) improve skimming of spilled oil in drift ice; b) clear oil from salt marshes; and, c) improve the effectiveness of dispersant application operations (Buist et al. 2010c).

Ohmsett experiments in 2010 on the use of herders as a rapid-response technique for use in open water (SL Ross 2012) showed that:

- On open water, in calm conditions, herders contain a slick for more than 45 minutes;
- On open water, in a non-breaking swell condition, herders restrain a slick, but the constant stretching and contracting of the herded slick by the waves elongates and slowly breaks it into smaller fragments; and
- Breaking or cresting waves disrupt the herder's monomolecular layer, and the oil slick itself, quickly resulting in many small unrestrained slicks.

Two herding agents (ThickSlick 6535 and SilTech OP-40) have been placed on the U.S. EPA National Oil and Hazardous Substances Pollution Contingency Plan (NCP) Product Schedule for consideration for use in U.S. waters and were commercially available as of June 2012. Samples of these herders have also been submitted to Environment Canada for consideration for use in Canadian waters and are under review. Additional details on these earlier experiments and herders in general may be found at: http://www.arcticresponsetechnology.org/wp-content/uploads/2015/05/Herder-Research-Summary.pdf

An application system, consisting of a pump, controls, and reservoir was designed for use from an appropriate helicopter. It incorporates a reel-able hose that is used to lower the application nozzle to the target elevation above the water for herder application. (Unlike dispersants, herders must be applied in a narrow swath on the water around the periphery of a slick to be effective.) Dry-land, static trials were conducted in September 2013 and successful full-scale (with 75 and 150-L crude oil slicks) helicopter flight trials, including herded slick ignition with a Heli-torch, were carried out in a shallow test basin in Alaska in 2015 (Potter et al. 2016). Figure 2.1 shows a collage of photos from these large-scale trials in Alaska.

In late 2015 development of an integrated herder application and slick ignition system for offshore helicopters commenced and is ongoing for IOGP. This project is scheduled to be completed in 2016.

Also in 2015, a large research project was carried out jointly with SL Ross and two universities in Denmark on the fate and environmental effects of herders in Arctic waters and on better defining the windows-of-opportunity for herder use in cold open water and loose drift-ice conditions (Buist et al. 2016). Laboratory experiments at SL Ross and CRREL (small-scale and meso-scale) on the Windows of Opportunity for the two commercially available herders with four different crude oils demonstrated that:

- The initial herded thickness achieved is a function of both herder and crude type;
- OP-40 was generally better than ThickSlick 6535;
- As the crude oils evaporated, in general, the herders became more effective, except when the evaporation caused the oil's pour point to increase to more than 8° to 10°C above the ambient temperature: at that point neither herder could contract the oil;
- Herders could contract lightly emulsified oil (25% water content), but not moderately emulsified oil (50% water);
- Low concentrations of slush ice on the water did not detract from the performance of the herders; but, the presence of high concentrations of slush ice prevents the herders from reaching the edge of the slick (and prevents the oil itself from spreading); and,
- Gentle, non-breaking wave action appears to assist with herding.

The fate and environmental effects experiments in Denmark involved the same two herders and two of the oils that had been tested at SL Ross. To summarize these results:

- Most of the herder around an oil slick remains on the water after the slick has been burned in situ.
- Very low concentrations (parts per billion) of herder can be detected in the water under the slick. These levels are several orders of magnitude less than the estimated toxicity concentrations of herders measured in lab tests.
- No detectable levels of herders were found in the smoke plume.

- ThickSlick 6535 herder may biodegrade quickly and will not bioaccumulate in high Arctic copepods. OP-40 herder does not biodegrade initially and may bioaccumulate in high Arctic copepod. Because of the challenges in measuring herder concentrations in water, these conclusions are tentative.
- Herders can affect seabird feathers by altering their water repellence, as do oil slicks and burn residue. Once the herder has spread out to a monolayer, which will happen quickly at sea, the potential impacts are greatly reduced. Herder films spread very rapidly on water and will quickly reach monolayer thickness because very small dosages are applied around targeted oil slicks. In a large oil spill the herder film will mostly replace oil slick and sheen on the water surface as it contracts the slicks. Herder monolayers will not persist on the water surface as they disperse very easily. The herder will start to lose effectiveness around 1 hour after application - depending upon weather conditions. Even so, the loss of oil slick contraction effectiveness is a gradual process.

Figure 2.1 Field Test of Helicopter Herder Application and Crude Oil Ignition.

(A) - Aerial view of test basin;

(B) - Herder application device with herder nozzle magnified in inset;

(C) - Application of gelled gasoline igniter via Heli-torch;

(D) - Free-floating ISB viewed from ground level observation point

(E) - Close up of free floating ISB

3 OBJECTIVE

The primary objective of the field experiments described in this report was to demonstrate the use of herders in open water conditions and validate the findings of an earlier field study of herders in conjunction with ISB. A secondary objective was to observe whether a herder monolayer could eliminate or significantly reduce the frequency of breaking waves in winds greater than 5 m/s (10 knots).

The main purpose with the upfront laboratory testing, performed by SINTEF, was to supply sufficient input data to the SINTEF Oil Weathering Model (OWM) for predictions of the weathering characteristics of Grane Blend, in addition to compare the emulsifying properties (water uptake) of Statfjord C with Grane Blend. SL Ross performed upfront bench scale herder testing of fresh and weathered Statfjord and Grane Blend crude oils to determine their behaviour when subjected to chemical herding.

Ecotoxicity testing of herders and herder components, performed by SINTEF, had the objective to assess the toxicity by use of tests being routinely used in Norway (*Skeletonema pseudocostatum* (phytoplankton) and *Acartia tonsa* (copepod)). Previous toxicity testing had been performed in the US by use of the shrimp *Mysidopsis bahia*.

4 UPFRONT LABORATORY TESTING

4.1 SL Ross laboratory testing with herder

Bench scale herder testing was performed on fresh and evaporated Statfjord and fresh Grane Blend crude oils to determine their behaviour when subjected to chemical herding. In summary, crude oil samples are weathered to a predetermined mass loss (for the Statfjord crude, 10% mass loss and 20% mass loss were selected) and these weathered samples, along with fresh crude samples, are included in a testing matrix. For this series of tests two samples of ThickSlick 6535 (TS6535) (one prepared by DESMI, and one prepared by SINTEF) are used.

The Herder Pan Test (HPT) consisted of placing a volume of water in a 1m x 1m pan, confirming the interfacial tension of the water, adding a volume of oil to the surface and then allowing it to spread to its equilibrium thickness. A volume of herding agent was then applied to the open water surface around the test slick and the slick was allowed to contract to a herded equilibrium thickness and monitored over the remainder of the one-hour test. Observations were recorded by digital photographs for image analysis to determine the oil slick coverage area. The effectiveness was reported as average slick thickness at periodic time intervals.

One herder (TS6535, as blended by SINTEF) was tested with each of fresh, 10% evaporated and 20% evaporated Statfjord crude.

These tests were performed with water at approximately 12°C (+/- 1.5°C), and salinity at 35‰. The specific procedure used for these experiments is:

1. Place 20L (depth of 2 cm) of chilled salt water in each 1-m^2 pan lined with freshly rinsed new plastic film.
2. A sample of the water is grabbed from the surface using a Petri dish to measure the water-air interfacial tension (IFT) using a DuNuoy Ring Tensiometer. If the IFT reading is less than 65, the water and film are replaced.
3. All fans, and other sources of air movement are temporarily halted (during the duration of the experiment).
4. A sample of approximately 500 mL of the test oil is poured on the water using a spill plate; making sure the oil does not stick to the bottom of the pan while being poured.
5. Signage is added to the side of the pan denoting test number, conditions and photo time which is visible in the photos.
6. The oil is allowed to spread to equilibrium and an initial overhead photo is taken for subsequent oil area analysis.
7. A prescribed amount (150 µL) of herding agent is applied to the open water areas around the perimeter of the spill with a micropipette.
8. The oil is allowed to contract and additional photos are taken after 1 minute, 10 minutes, 30 minutes, and 1 hour.

Below (see Figure 4.1) are the results of the 1-m^2 pan tests with ThickSlick 6535 on 35 ppt salt water at 12°C with fresh, 10% and 20% evaporated Statfjord crude and fresh Grane Blend crude. In summary:

- the fresh and 10% evaporated Statfjord crude are herded effectively by the SINTEF-blended ThickSlick 6535.

- the 20% evaporated Statfjord is not as effectively herded as the fresh and 10% evaporated Statfjord, and may be beginning to show pour point effects with the herder (according to the SINTEF modelling, the pour point of Statfjord crude in the test slick would be approaching 12°C at this point).
- the SINTEF blend of ThickSlick 6535 is slightly more effective than the DESMI blend on the fresh Statfjord crude, producing about 0.5 mm more thickness of the herded slick over the test time.

The fresh Grane Blend crude is appreciably better for herding than the fresh Statfjord crude. Experience with the Grane Blend crude in previous tests (Buist et al 2016) with TS 6535 indicate that this advantage will be maintained as Grane Blend evaporates and begins to emulsify.

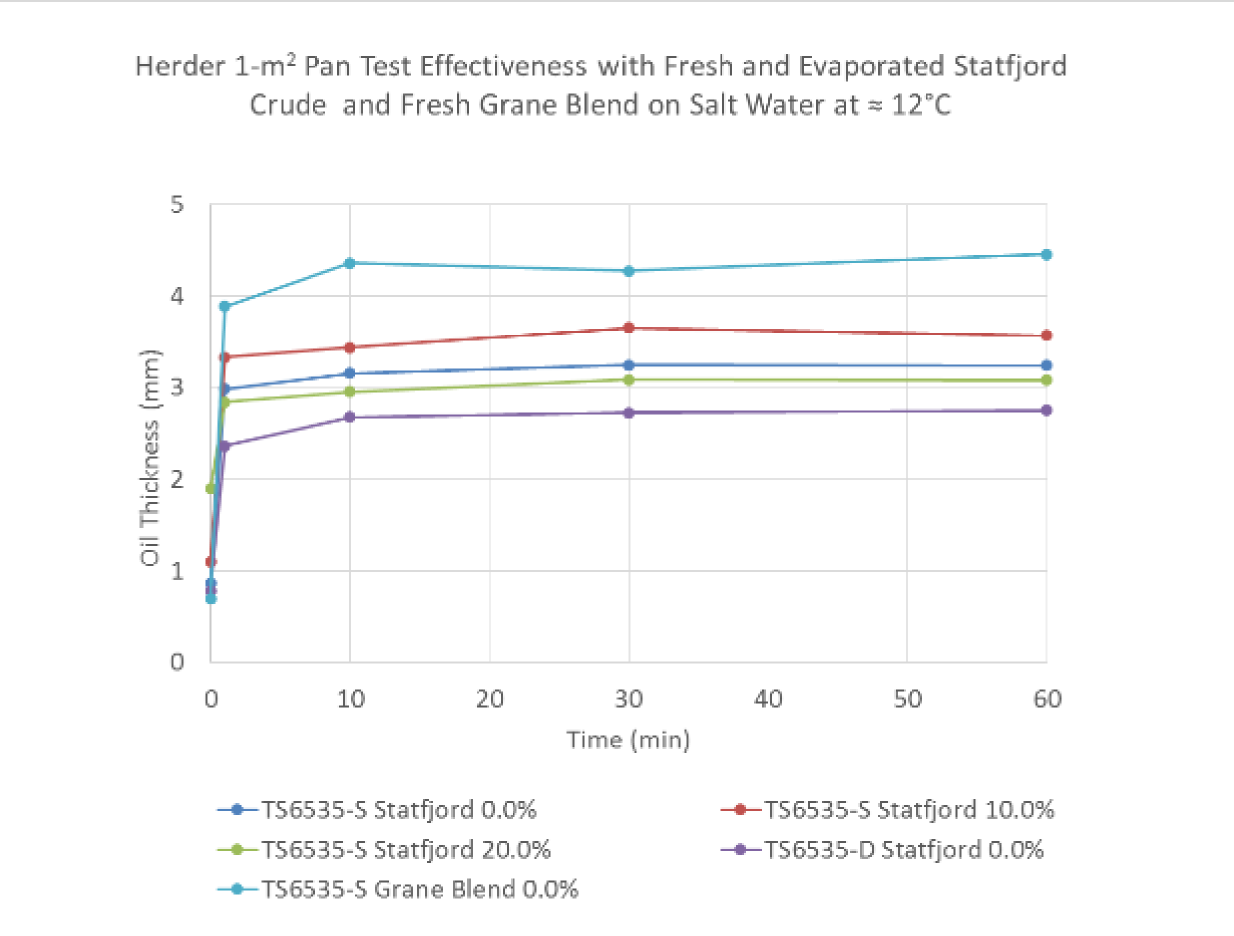


Figure 4.1 Bench Scale Herder Effectiveness Testing

4.2 SINTEF laboratory testing of Grane Blend crude oil

In order to find a test oil appropriate for the herder and ISB field experiments, laboratory testing of weathering properties of Grane Blend crude oil was performed and compared to a limited testing of emulsifying properties of Statfjord C crude oil which also was a candidate for the field testing. Sørheim and Johnsen, 2016, reported the results from this study to IOGP. Combined with the herder testing in 4.1 this contributed to support for the decision of test oil to be used.

The present Grane Blend crude oil is a blend of Grane, Svalin and Edvard Grieg oil fields in the North Sea. The Grane Blend is transported by pipeline to the Sture terminal for storage and export. The limited weathering characterisation performed included:

- Distillation /topping the Grane Blend oil into: 150°C+ / 200°C+ / and 250°C+ residues
- Physico-chemical characterization of fresh and topped residues
- Emulsifying properties (incl. water uptake rate, max-water, viscosities) at 13°C
- Weathering predictions: The weathering data generated were used as input data to oil weathering model in order to generate weathering predictions at different wind speeds and temperatures.

Table 4.1 shows some physical data for Grane Blend, which is a relatively high density crude oil (compared to other Norwegian crude oils). Figure 4.2 shows the GC/FID chromatogram for the fresh oil indicating that it has a paraffinic nature (high fraction of n-alkanes). Some of the more complex components, shown as a broad and poorly defined bump below the sharp peaks, are often described as "Unseparated Complex Material" (UCM). Heavier compounds such as asphaltenes (> nC_{40}) are not possible to analyse with this technique, but previous analyses of "pure" Grane crude oil indicate that it may be an asphaltene-rich oil.

Table 4.1 Physical parameters of Grane Blend, 2016.

Oil type	Residue	Evapo-rated (vol. %)	Residue (wt.%)	Density (g/mL)	Flash Point (°C)	Pour Point (°C)	Visc. 13°C mPas, 10 s^{-1}
Grane	Fresh	0	100	0.899	-	-3	64
Blend	150°C+	9.8	92	0.919	45	-6	217
2016	200°C+	18	85	0.931	90	3	569
	250°C+	26	78	0.941	121	9	1856

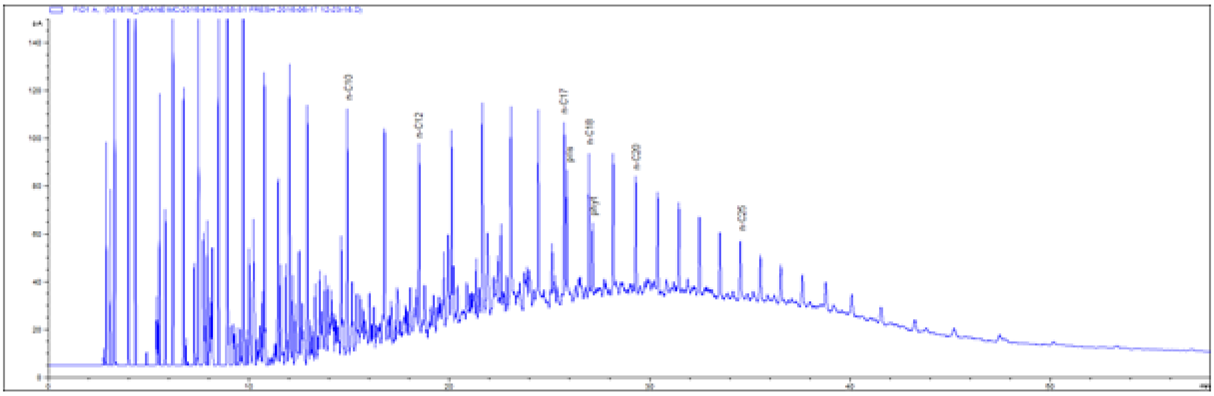


Figure 4.2 GC/FID chromatograms for the fresh oil samples of Grane Blend (2016).

Figure 4.3 is an example of a prediction from this study giving the evaporative loss of Grane Blend. At 5 m/s wind the evaporation is predicted to be below 10 % within an hours after release, which is the approximate time between release and herding/burning of the slicks during the field trial.

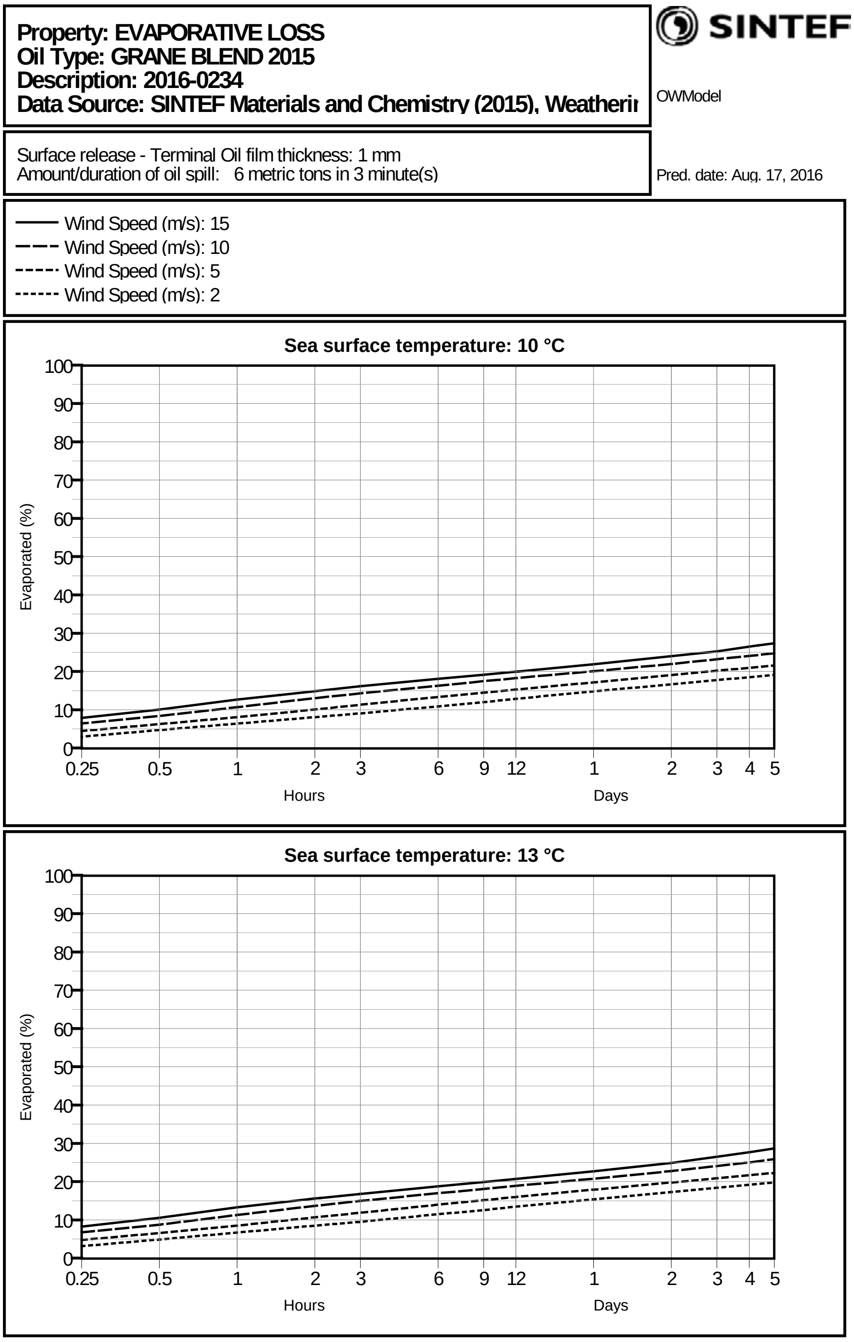


Figure 4.3 Evaporative loss of Grane Blend crude oil predicted at sea temperature of 10 and 13 °C

The light paraffinic crude oil Statfjord C (density of 0.834 g/mL) was assumed to be a possible candidate for use for the herder & *in-situ* burning (ISB) experiments. However, the emulsifying properties showed that Statfjord C reached a higher water uptake compared with Grane Blend. The crude oil with the lowest water uptake was assuming most optimal for those experiments, hence, Grane Blend was regarded as the most appropriate test oil for use in the field trial compared with Statfjord C. For more information, see Sørheim and Johnsen, 2016

4.3 Ecotoxicity testing of herders and herder components

Acute toxicities of two herders were tested with two marine species; the phytoplankton *Skeletonema pseudocostatum* and the copepod *Acartia tonsa*, according to the guidelines ISO/DIS 102053 (phytoplankton test) and ISO 14669 (copepod test). These organisms represent different trophic levels in the marine food chain. The ecotoxicity testing included a hydrocarbon-based (ThickSlick 6535) herder, a silicone-based (Siltech OP-40) herder, a fresh ThickSlick prepared at SINTEF, and the dispersant Corexit 9500A. Thickslick 6535 was also re-tested in the *Skeletonema*-test, together with its components sorbitan monolaurate and 2-ethyl-1-butanol.

Figure 4.4 shows an example of results from this study giving survival curves from the *Acartia tonsa* test for four different samples.

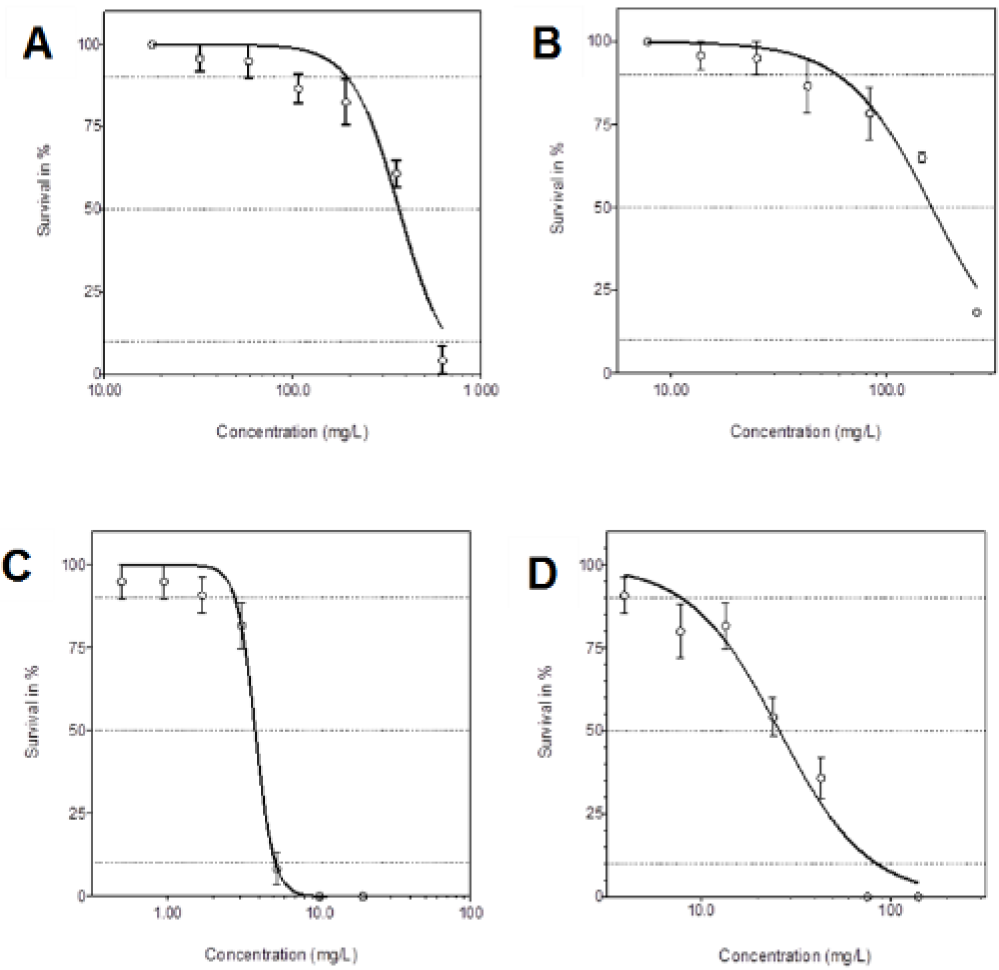


Figure 4.4 Survival curves of A. tonsa exposed for 48 hours to original ThickSlick 6535 (A), ThickSlick prepared by SINTEF (B), Siltech OP-40 (C), and Corexit 9500A (D).

All the results from this study are presented in Brakstad and Altin, 2016. The main results are presented in table 4.2 and discussed below.

Table 4.2 Summary of the main findings from the ecotoxicity study.

Test substance	*S. pseudocostatum* EC50 ± 95 % CI (mg/L)	*A. tonsa* LC50 ± 95 % CI (mg/L)
ThickSlick 6535	2.52 (1.94-3.26)	368.4 (328.0 – 413.8)
Thickslick – prepared at SINTEF	6.68 (4.54-9.83)	161.5 (139.6 – 186.9)
Siltech OP-40	4.29	3.81 (3.50 – 4.15)
Corexit 9500A	12.76 (9.93-16.37)	26.0 (21.7 – 31.0)
ThickSlick 6535 - Re-test	4.27 (3.67-4.98)	Not tested
Sorbitan monolaurate	3.12 (1.08-9.03)	Not tested
2-Ethyl-1-butanol	320.6 (283.1-362.2)	Not tested

In the phytoplankton test, the acute toxicities were of the same magnitude for the herders. The acute toxicity of the silicone-based herder Siltech OP-40 was similar for the two organisms (Table 1 and Table 2). Siltech OP-40 showed moderately higher toxicity than Corexit 9500, but were significantly more toxic than ThickSlick 6535 in the copepod test. However, Thickslick 6535 had an order of magnitude lower toxicity than Corexit 9500 in the copepod test. The acute toxicity of ThickSlick was attributed to the surfactant sorbitan monolaurate rather than the solvent 2-ethyl-1-butanol. The copepod results for ThickSlick 6535 was comparable to the acute toxicity of the same substance to the marine shrimp *Mysidopsis bahia* (LC_{50} of 286 mg/L)(https://www.epa.gov/emergency-response/thickslick-6535). The toxicity results with ThickSlick 6535 in the phytoplankton and copepod tests were comparable with corresponding results with the freshly prepared version of this substance prepared at SINTEF.

A re-test of the original ThickSlick 6535 also demonstrated that the phytoplankton test showed reproducible toxicity results.

The acute toxicities of the original herders were slightly higher than the acute toxicity of the dispersant Corexit 9500 in the phytoplankton test. However, the results for the SINTEF-made preparation of ThickSlick and Corexit 9500 resulted in comparable phytoplankton toxicity.

To put these values into perspective, the lowest EC50 values are typically in the same range as the toxicity of the non-diluted water-soluble fraction of a moderately weathered crude oil. It should also be emphasized that the environmental impact of the tested substances is mainly governed by the specific toxicity (EC50/LC50) and the environmental concentrations resulting from the amounts used. When comparing the potential environmental impact of herders and dispersants it is therefore crucial to consider both the toxicity and the relative volumes used.

Although this was strictly a toxicity study, an important consideration for assessing the environment performance of the two herders is the amount of each product required to treat an oil slick of a given size. As we understand, the amount of herder applied to an oil slick could be one - two orders of magnitude less than needed to disperse it. For more information see: Brakstad and Altin, 2016.

5 WORK PLAN AND HSE PLAN FOR THE FIELD EXPERIMENTS

5.1 Main project tasks

The goals were met by undertaking eight tasks:

1. **Obtain Necessary Permits:** NOFO was responsible for preparing and issuing the discharge permit application to the Norwegian Environmental Agency. Within this project SINTEF had primary responsibility for preparing input to NOFO, with SL Ross providing technical support where necessary, for the acquisition of all permits required for the HISB experiment including herder use approval, test location, number and size of releases, types of crude oil, conduct of the burns, and disposal of any test materials remaining.
2. **Develop and Refine a Field Experiment Test Plan:** A detailed field experimental plan was drafted and refined based on IOGP JIP comments.
3. **Provide Input and Revisions to a Field Experiment HSE Plan:** A key component of the overall project was the HSE plan that covered all identified hazards along with their mitigation. The project team produced and revised an HISB-specific risk assessment matrix and provided input to NOFO, who developed the overall field exercise HSE plan. This plan went through several stages of internal review and approval before testing began.
4. **Preliminary lab-scale testing of crude oil properties and herders prior to the experimental release:** Prior to conducting the experimental release, SINTEF performed laboratory-scale experiments to characterize the spill-related properties of the Grane Blend crude. SINTEF and SL Ross independently verified that Grane Blend crude is amenable to herding and burning when fresh, and after weathering for a short time. SINTEF performed ecotoxicity testing of herders and herder components.
5. **Strategy, technical planning and coordination of the monitoring and remote sensing aspects:** The University of Bergen, assisted by SINTEF and SL Ross, designed the operational monitoring and provided input to the remote sensing plan to document the spreading, herding, ignition, and burning of the three primary experimental oil slicks.
6. **Strategy, technical planning and coordination of the smoke plume sampling aspects:** The University of Bergen (UiB) and SINTEF, with advice from SL Ross, designed the operational smoke plume sampling plan to document the key constituent(s) of concern to human health in the smoke plume from a successful burn.
7. **Field Experiments:** SL Ross planned and carried out the HISB component of the 2016 NOFO Field Trials, including applying the herder from small boats, igniting the slicks with gelled gasoline igniters, and supervising the recovery of residue from experimental slicks that were ignited. SINTEF provided assistance in the planning of the experiment and had operational control of the tests.
8. **Write technical report, and contribute to a peer-reviewed scientific paper and technical presentation:** The final task involved coordination and preparation of a final project report documenting the rationale, methods, results, conclusions, and recommendations arising from the study. A concise overview article for publication and presentation at a major oil spill response conference will also be prepared.

5.2 Organisations participating in the field trial

The following organizations were involved with the HISB field experiments:

NOFO

These field experiments were conducted as a part of a larger NOFO offshore field trial (OPV-2016) that entailed:

- Testing of mechanical oil spill response (OSR) equipment with 150 m^3 of emulsion:
  - Experiment 1 – Testing Integrated pump system for NOFI Current Buster 6
  - Experiment 2 – Testing of DESMI "Pre-boom"
- Releases of free-drifting oil slicks:
  - Experiment 3 – Thin Oil Films (TOF). In total, four releases (10 m^3 each of Åsgard Blend light crude/condensate blend)
  - Experiment 4: Herder and in situ burning (HISB). In total three releases (target: 6 m^3 each of Grane Blend crude)
- NOFO designed and operated the oil release system.
- NOFO was responsible for arranging the vessels, remote sensing aircraft, permits and funding of experiments 1and (vessel support was provided by the Norwegian Coastal Administration (NCA) and the Norwegian Coast Guard; aircraft were provided by NCA, Finnish Border Guard/SYKE, and Netherlands Coastguard.
- Experiment 3 was financed by the Norwegian Research Council and seven oil companies, and Experiment 4 was funded by the International Association of Oil and Gas Producers (IOGP) Joint Industry Programme (JIP).
- NOFO was responsible for conducting Experiments 1 and 2 and providing co-funding and logistical support for Experiments 3 and 4.
- Developed and implemented the HSE Plan for all the experiments.

The International Association of Oil and Gas Producers - Arctic Response Technology JIP

- Funded and administered the participation of SINTEF, SL Ross, Maritime Robotics, University of Bergen and other subcontractors in Experiment 4
- Provided two onsite representatives (Dr. Tim Nedwed and Mr. David Dickins)
- Reviewed and approved the test plan, HSE Plan and draft and final reports and scientific/technical papers and presentations.

SINTEF

- Main contractor responsible for administering the various subcontractors (SL Ross, Maritime Robotics and University of Bergen) for Experiment 4
- Coordinated the planning and logistics for Experiment 4
- Provided personnel to assist with Experiment 4
- Prepared the Test Plan with SL Ross and contributed to the HSE Plan
- Directed sampling of the smoke plume by an Unmanned Aerial Vehicle (UAV-drone) and an Unmanned Surface Vehicle (USV)/OceanEye® MBS (Moored Balloon System)
- Provided hand-held garden sprayers and materials (gelling agent, gasoline, flares) for hand-held ad-hoc gelled gas igniters.

- Provided sorbent materials (pads and booms), heavy-duty garbage bags, plastic tarpaulins, disposable PPE, suitable waste container(s), etc. for residue recovery operations and/or unignited oil recovery

SL Ross Environmental Research Ltd.

- Directed each HISB (Experiment 4) individual trial
- Arranged for the herding agents to be shipped from DESMI to NOFO
- Directed Maritime Robotics in use of OceanEye® MBS and UAV video drones during HISB experiments
- Provided "solid stream" 0002 nozzles for herder spraying
- Filled and pressurized garden sprayers with ThickSlick 6535 and applied herder.
- Manufactured ad-hoc hand held igniters and deployed into experimental slicks
- Directed recovery of any burn residue
- Provided and operated weigh scales to determine amounts of herder applied and residue weights recovered
- Assisted with the test equipment operation during the tests
- Collected copies of data from other subcontractors and SINTEF, including aerial digital photos and HD video, weather and oceanographic data, GPS position data, aerial remote sensing data, amounts of oil released and release timing, smoke plume sampling data,
- Analysed data
- Drafted the final report and contributed to a technical paper for planned presentation at the International Oil Spill Conference and Exhibition (IOSCE).

Maritime Robotics

- Provided two drones with operators to be used in concert with each other to minimize grounded time and efficiently carried out the operational surveillance/decision making and documentation for HISB slick spreading, herder application ignition timing and burn measurements
- Provided one drone with operator to sample the ISB smoke plume
- Provided one USV carrying an OceanEye® MBS with operator for video surveillance and for surface level smoke particulate sampling after a successful ignition

DESMI

- Provided 40 L each of ThickSlick and Siltech OP-40 in cans or plastic containers shipped to NOFO base in Tananger

University of Bergen

- Performed smoke plume sampling: analytical parameters; human exposure; sampling etc.

5.3 Test personnel

The test personnel assignments are listed in table 5.1.

5.4 Permitting

In February 2016, NOFO sent an application to the Norwegian Environmental Agency (NEA) for scientific releases of oil in connection to the NOFO Oil-on-water field trials in week 24/25, 2016). The application included the following experiments:

Testing of Mechanical equipment (total amount to be spilled: 150 m^3 of weathered crude oil emulsion):

1. Integrated pump-system for NOFI Current Buster 6
2. DESMI Perforated boom.

TOF and Herder/ISB Experiments:

3. Thin Oil Films (TOF) – four releases (total 40 m^3, Åsgard Blend Light crude oil)
4. "Herder and in situ burning – HISB - three releases (total 18 m^3, Grane Blend crude, and a total of 17 L of Herder- ThickSlick 6535)

As part of the application, SINTEF and SL Ross submitted a detailed description of the justification, goals, experimental plans, monitoring plans, and limiting criteria for the HISB experiments. After a hearing period at NEA and fishery agencies, NOFO received the approval from the NEA April 19th. The approval was generally positive; however, it contained some specific requirements to be fulfilled in the HISB releases:

- Sampling of surface oil to document film thickness and physico-chemical properties;
- Documentation and analysis of soot particles from the smoke plume; and
- Plan for recovery of burn residue.

Prior the field trials, a supplementary plan was therefore developed including use of sorbent booms for surface containment and special nets for recovering and lifting the residue and the sorbent booms into trash containers on the deck on the response vessel. Equipment for measurements of soot particles was acquired.

Table 5.1 Test Personnel Assignments

Affiliation	Name	Role
IOGP	David Dickins	Technical Working Group co-Chair
	Tim Nedwed	Technical Working Group co-Chair
NOFO	Svein Henning Lysgaard	Operations Director
	Hans V. Jensen	Advisor R&D
	Frode Engen	Team Lead R&D
	Evy Hesjedal	On-Scene Coordinator
SINTEF	Per Daling	Lead Researcher/Principal Investigator/Deputy Project Manager
	Ivar Singsaas	Project Manager
	Kristin Rist Sørheim	Co- Project Manager
	Daniel Franklin Krause	Air Sampling Manager
SL Ross Environmental Research	Ian Buist	Principal Investigator
	Steve Potter	Team Lead and HISB Field Experiment Director
	David Cooper	Senior Engineer and co- HISB Field Experiment Director
DESMI	Peter Lane	Herder Supplier
Maritime Robotics	Eirik Hovstein	Direct UAVs (drones) and USV – Aerostat for experiment surveillance coverage and smoke sampling
	Morten Einarsve	Drone operator
	Andreas Misje	Drone operator
	Lars Steffenrem	Drone operator
University of Bergen	Magne Bråtveit	Responsible for Air Sampling Protocol &Analysis
	Ingrid Gjesteland	Air sampling, PhD student.
	Erlend Sunde	Air sampling

5.5 HSE plan and requirements

NOFO was responsible for preparing and implementing an overall robust HSE plan for the field trial. The objectives of the HSE plan was: "*to conduct all of the operations without personal injuries and without damaging the environment and equipment. It is therefore a prerequisite that all parts of the individual activities is characterized by a good health, environment and safety culture. This is needed to succeed with the systematic work that is necessary to avoid dangerous situations or that unwanted situations occurs.*

The Exercise Director management is responsible to supervise and facilitate conditions to conduct activities under the field trial in a safe way, so that personal injuries and/or unnecessary damages to environment and equipment will be avoided. It is the individual participant's responsibility to follow the HSE requirements and instructions that are given. The staff on board the vessels involved shall in addition follow the vessel safety instructions. Nothing in the HSE plan hampers the individual participant to communicate the need for, or initiate additional actions to improve safety during the conduction of the exercise".

How HSE was addressed

- HSE plan as Attachment A of the overall Operations plan
- Risk assessment forms
  - Hazid overall risk assessment
  - Hazid drone operations
  - Risk assessment for use USV and MOB boats
  - Risk assessment for oil release arrangement on-board KV Sortland
  - Risk assessment for experiments 3 (Thin Oil Films) and 4 (Herders and ISB)
  - Risk assessment for operations by remote sensing aircrafts
- Safe Job Analysis (SJA) was regularly conducted during the execution of the field trial before work on deck was started.

In addition to requirements specified in the HSE document and manual "Oil Spill Contingency, the following requirements was specified regarding conduction of Oil on water field trial 2017:

<u>General:</u>

- Fire-, lifeboat instructions and familiarization with safety routines will be conducted on all vessels immediately before departing to the site Frigg field. Survival suits for everyone shall be available on board.
- The safety meeting/briefing with practicing personnel shall be conducted before any of the activities are initiated.
- Job Safety Analysis (JSA) shall be performed before work on deck is started. That is in particular relevant for work that e.g. has not been sufficiently described or controlled by a procedure or by former risk assessment analysis, or if a new method or equipment is used that is not described in an existing procedure or routine. JSA is conducted in agreement with JSA method described in the HSE document or the vessels' JSA procedure.
- Individual participants shall have familiarized with safety data sheet for oil emulsion and dispersant agents, which shall be available. Special focus shall be paid to which protection measures are necessary.
- Each participant is responsible to take care of its own safety and contribute to the personal safety of colleagues.
- Provide good communication via radio communication has to be ensured between the bridge and workers on deck, in the MOB-boat, aircraft, helicopter and others (see also communication plan attached to the operation order).
- Gas meter shall be available on board the vessels.

<u>Mobilization/demobilization:</u>

- In case of mobilization/demobilization attention shall be paid when heavy parts and hanging weights are lifted, including avoiding crush injuries.
- Correctly and approved lifting equipment shall be used and checked before use.
- Please also see instructions and procedures at the base area.

<u>Work on deck:</u>

- Safety instructions of the vessel shall be followed.

- During work on deck with open port/porthole or on the MOB-boat, survival suits and/or safety vests (equipped with light) shall be used.
- Light conditions are supposed to be acceptable during working operations.
- Equipment intended for use during the training and stored on deck, shall be secured.
- When booms are deployed or retrieved, special attention shall be paid to hawser, ropes, and cables, located on deck. As few as possible (only authorized personnel) shall be present on deck during such operations.
- All staff shall use required and approved safety equipment according to NOFO's and the vessel's safety instructions.
- There shall be a suitable set-up for personal washing, and clean protection equipment shall be available where personnel is working with oil.
- A separation must be established between contaminated and clean areas to avoid secondary contamination and spreading of oil inwards the vessel. NOFO washing containers shall be used if available on board the vessel.
- Attention shall be paid for oil spillage, hydraulic fluids, dispersants agents, etc., with respect to slip hazard. Use your personal safety footwear. Focus on tidiness and use bark and/or oil absorbing mat where it is necessary.

Competence and training

Meetings were arranged with all participants to go through the HSE requirements and work with risk assessment forms. Participants abroad participated by Skype/telephone prior to the field trial and in person during mobilisation at the base and on-board the vessel.

For participants and observers during OPV 2016 the following competences/documentation was required:

Participants:

- Maritime health certificate (seafarer's health certificate)
- STCW (Standards of Training, Certification and Watchkeeping for Seafarers) Basic Safety training

Observers:

- Maritime health certificate (seafarer's health certificate)

HSE status from the field trial and lessons learned

All operations during the field trial were safely conducted and no accidents or injury was reported. A "Summary of lessons learned" was prepared shortly after the field trial. Among the most important observations that may be related to HSE, the following points are highlighted:

- People on-board the MOB boats were not using respiratory protection all the time. However, it might not necessarily be a requirement working up-wind oil slicks or in gas-free areas.
- A remote sensing aircraft had a low flight over on day 2 without Strilborg bridge or drone pilots being informed on beforehand. It could potentially have caused a conflict between aircraft and drone, but no drones were operating at that point.
- Communication between MOB boats and mother vessel was not optimal at all time. Modification or changing of plans was not always communicated with all involved personnel. Deviations in plans need to be better communicated in future field trials.

- An effort to recover burn residue was performed without much success. The residue was floating extremely heavy in the water and would easily have submerge under any boom shirt. Even if burn residues are recognised as relatively inert, there is a need for improvement of technology and methods prior to future similar field experiments.

6 TEST INFRASTRUCTURE AND PLANS

6.1 Participating vessels

Two response vessels (contracted by the Norwegian Coastal Administration – NCA) were allocated specifically for the TOF and the HISB experiments:

KV Sortland: Is a Norwegian coastguard vessel (in operation from 2010) within the "Barentsea-class". The vessel is 93 m long and 16.6 m wide. KV Sortland was operated as a command vessel during the NOFO OPV 2016. The vessel was responsible for the oil releases for the TOF and HISB experiments. Additionally, an unmanned surface vessel (USV) with an Aerostat (OceanEye® with visual and IR video cameras) were stationed and launched from KV Sortland. The USV and Aerostat was operated by Maritime Robotics. Further details are given in: http://www.maritimerobotics.com/

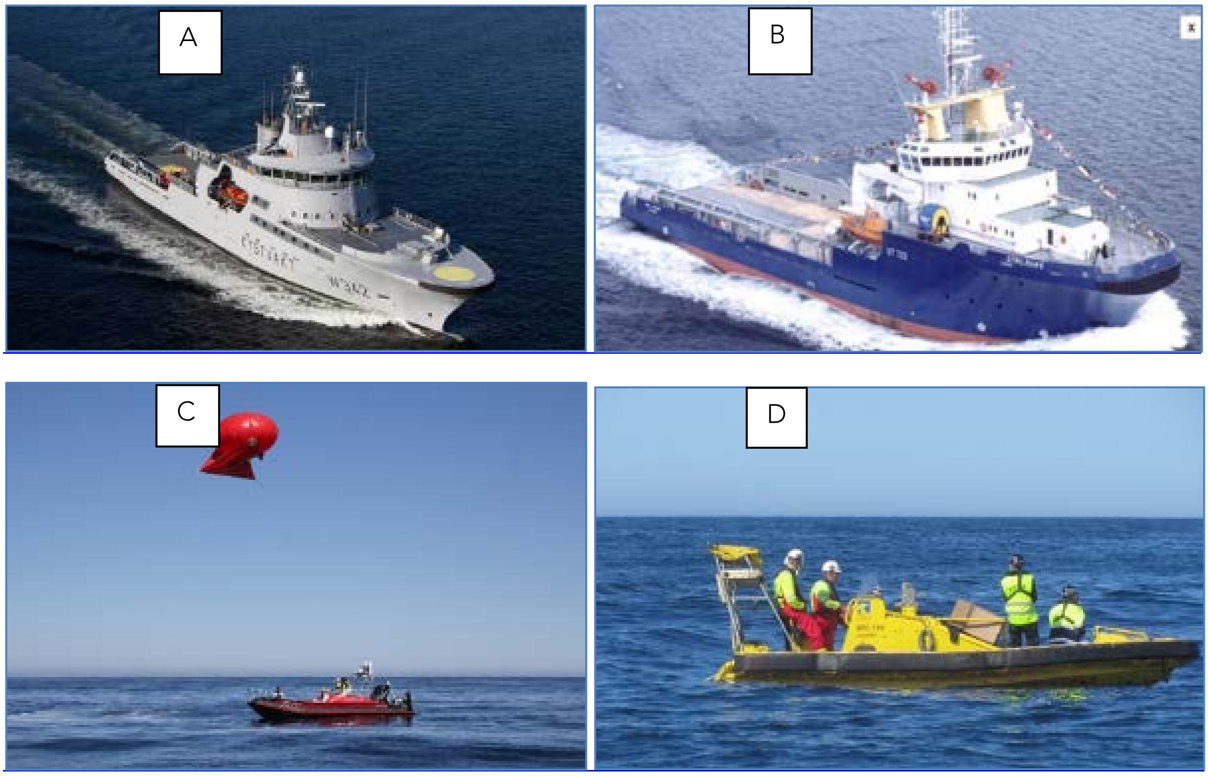


Figure 6.1 The two vessels involved in the HISB experiments. A: KV Sortland (command vessel), B: MS Strilborg , C: USV with Aerostat, D: Sampling boat (MOB boat on Strilborg)

MS Strilborg is a supply and response vessel, presently under contract for NCA as an emergency tow-vessel. Strilborg is 74.9 m long and 18 m wide. The two MOB boats on Strilborg (GTC 700, 7.2 m long), were both used for ground-truth sampling (surface oil and water column), air monitoring, the herding and ignition operations, and in containment and recovery of burn residue.

6.2 Oil discharge, Slick monitoring

The Grane Blend crude was released from the coastguard vessel KV Sortland (see Figure 6.1*Figure* , A), using a 60 m long hose, stretched out from the side of the vessel by a line from a MOB-boats (green circle, Figure 6-2, C and D). The oil was released gently on the sea surface through a special constructed floating weir system at the end of the hose (red circle). The release point was about 50 m away from the vessel, and avoided the oil drifting into the side of the vessel during the release. The oil was pumped out at a rate of 2 m^3 /min. as a point release (Figure 6-2,B). The rationale for the release set-up, was based on spreading simulations.

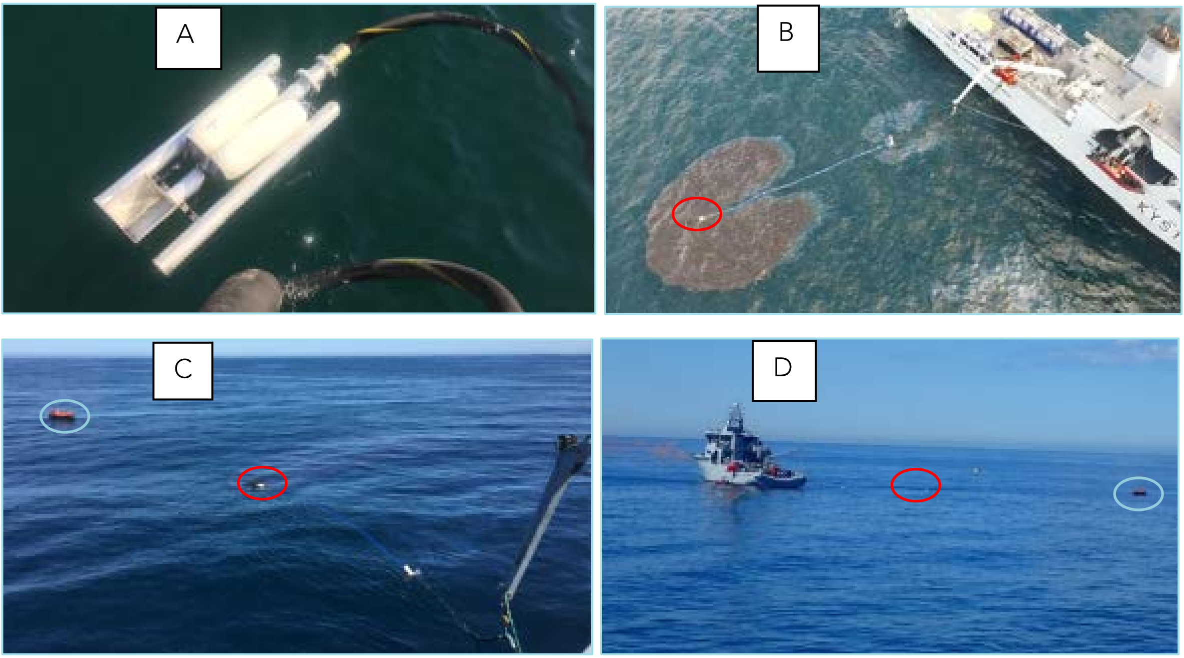


Figure 6.2 Release arrangement and configuration

(A) - Release arrangement: Floating weir system;

(B) - During release. Grane Blend pumped through a 50 m hose to the side of KV Sortland;

(C) - The release point was about 50 m from the vessel (red circle), stretched out by a MOB Boat (blue/green circle)

(D) – Alternative view of release point configuration.

For each experiment the required amount of oil (6 m^3) was planned transferred from the 18 m^3 crude oil shipping tank to a 30 m^3 "day" tank. The "day" tank had a discharge outlet slightly above the bottom of the tank and a remaining 2 m^3 would always be in the tank after pumping out. For that reason 2 m^3 in excess of the required volume was pumped to the "day" tank before each discharge. However, due to this the last discharge was only 4 m^3, with 2 m^3 oil remaining in the "day" tank. 1 cm depth in the "day" tank accounts for 100 litres of oil, and even if there are some uncertainties it is a good estimation that 6, 6 and 4 m^3 of oil was released in the 3 experiments respectively.

One of the MOB-boats on Strilborg (designated MOB-B) was primarily allocated for surface oil sampling and water column monitoring, with the following instrumentation:

- Surface oil slick thickness measurements (synchronized to aerial survey; see Figure 6.3):
    - o > 3 mm: use of a Plexiglas oil/water sampler. Visual measurements on site
    - o < 3 mm: PP-pad. Gravimetric quantification
- < 3 micron: Teflon net (Post-lab by GC or spectrophotometric quantification)
  Surface sampling for physical/chemical characterization of properties
    - o On site: viscosity, water content, emulsion stability, dispersibility (FET Test)
    - o Post lab. Analyses: rheology: yield stress / viscosity, evaporative loss, density etc.)
- Sampling of burned residue (density, viscosity, GC)
- Water column: oil concentration (UVF / chemistry) , in-situ particles (oil droplet) size measurements (LISST-100)

6.3 Herder application, Igniters

During the voyage out to the test site the herder was reconditioned after shipping. This entailed heating the TS6535 in the shipping cans and thoroughly shaking the warmed contents to re-dissolve

any precipitated surfactant into the solvent. Prior to each HISB experiment, 6 L of reconditioned herder was loaded into each of four pressurized garden sprayers (Figure 6.4). Two garden sprayers (Shixia model SX-CS8F) were allocated for use in MOB B and two for MOB C, with each MOB vessel responsible for the application of 3L per test run. This was done to ensure redundancy in each of the MOB vessels, and to enable one of the vessels to carry out the application of 6L of herder fluid during a test run if technical problems occurred with the other vessel. The maximum permitted overall volume of herder for the HISB experiments was 17 L. A description of TS6535 is contained in Appendix A.

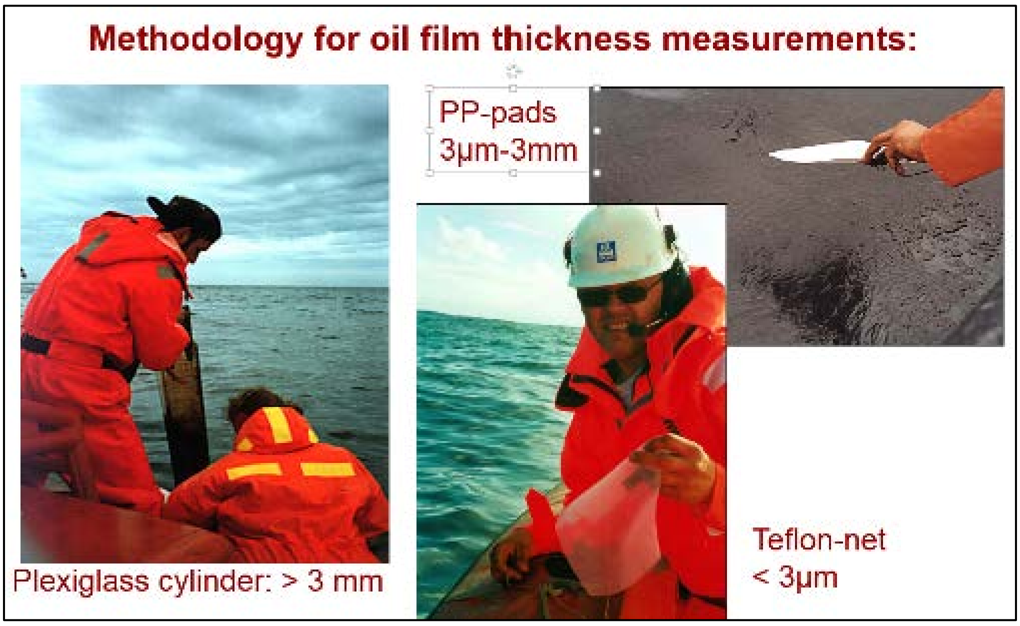


Figure 6.3 Methodologies for measuring oil slick thicknesses

Figure 6.4 Pressurized sprayer

Figure 6.5 Gelled gasoline/flare igniter

Hand-held igniters were assembled on board the MS Strilborg prior to the test runs. The igniters comprised a marine flare with supplemental floatation, ballast, and gelled gasoline attached. This design (see Figure 6.5) was based upon previous validation testing that took place in Canada. A total of 15 were initially constructed for the planned three burning runs.

6.4 Residue sampling

A 25 m long sorbent boom (Ecosorb ® Oil R Boom, AllMaritim AS) was used to contain the burned residue following the burns (Figure 6.6). The boom diameter is 20 cm with a 25 cm skirt. The boom comprises an outer sleeve of netting containing sorbent fibres, all made of polypropylene. A "lifting net" (10 m x 10 m, produced by Egersund Trål) was used for lifting the sorbent boom and confined oil residue from the sea surface into a trash container on the Strilborg. The net was surrounded by a 10 mm "frame rope" equipped with floating fenders on three of the sides and weights on one side (Figure 6.6).

Figure 6.6 Training by the MOB boats crew in operating the sorbent boom and the lifting net

6.5 Air sampling

The primary health concern in emissions from burning of oil is related to particles, Polycyclic Aromatic Hydrocarbons (PAHs) in the soot, and the gaseous emissions. The particle fraction PM2.5 was measured by a SidePak™ Aerosol Monitor AM510, which is a real-time monitoring logging instrument weighing about 0.5kg. It has built-in impactors for 1.0, 2.5, 10-micron cut off sampling. For this project the 2.5 micron impactor was used. Results are given in $\mu g/m^3$.

Figure 6.7 SidePak™ Aerosol Monitor AM510 with built-in impactor for real-time monitoring of PM2.5.

<u>PAH and BTEX</u>

When organic compounds are present as a combination of aerosol and vapour the standard method of air sampling is a "sampling train" which is a system that samples both aerosol and vapour of the relevant compounds (Figure 6.8). This consists of a combination of a 37mm filter-cassette with a glass-fibre-filter for sampling with aerosol/particles in series with an adsorbent tube for sampling of vapour (BTEX). The sampling cassette is attached to a pump with an air flow rate of 2.0 L/min. Two sampling cassettes were attached to one pump with a total weight of about 900g.

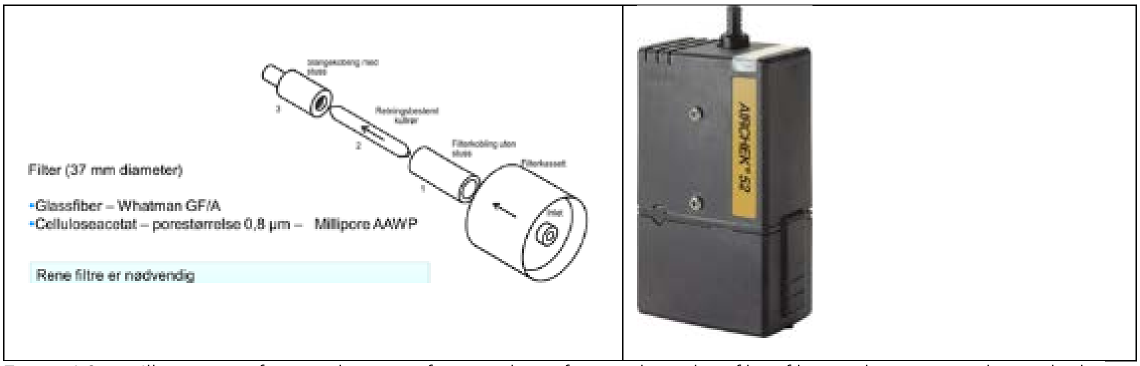


Figure 6.8 Illustration of a sampling train for sampling of aerosol on glass-fibre-filter and vapour on charcoal tube (left on figure), and a sampling pump (right on figure).

6.6 Video monitoring and air-sampling from drones

Maritime Robotics AS provided drone flight support to document the different aspects of the HISB experiments:

- Two video drones (DJI Inspire 1, specifications in Figure 6.10*Figure*)
- One drone (MR QUAD, specifications in Figure 6.10) with the same smoke sampler equipment for soot and BTEX / PAH (see Figure 6.7*Figure* and Figure 6.8*Figure*) for collecting samples in the smoke plume during the burning.

The drone operations performed by Maritime Robotics during the field test (both camera drones and sampling drone) are summarized in Appendix B.

Figure 6.9 Specification of the two video drones used

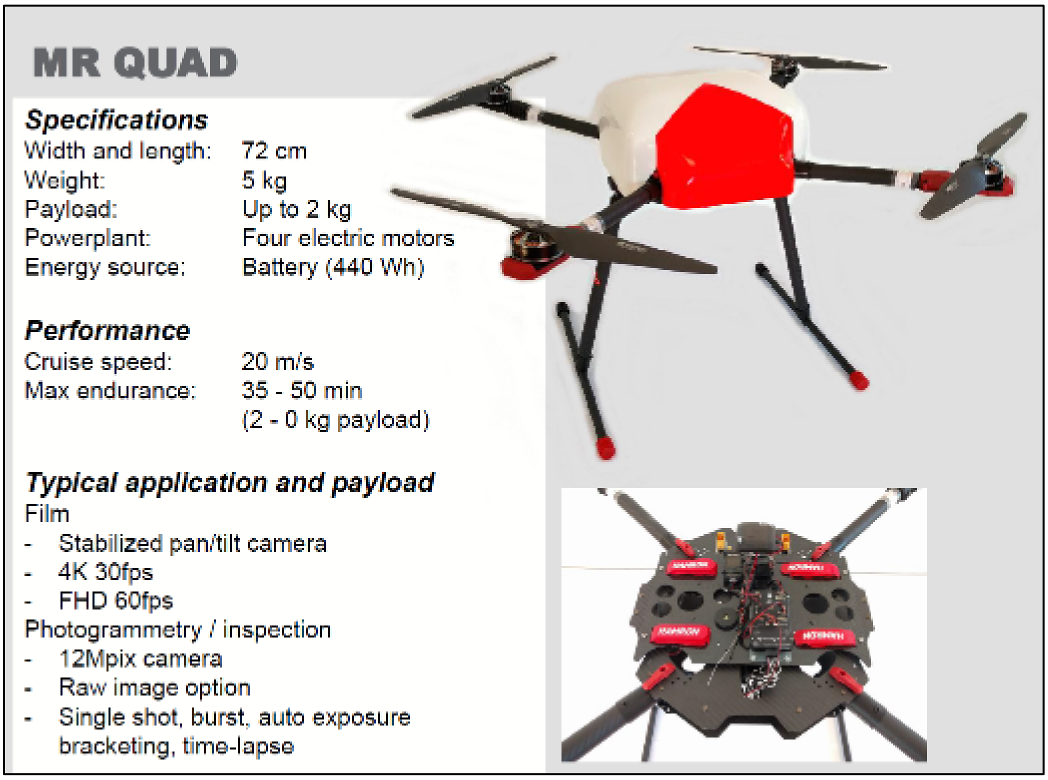


Figure 6.10 Drone specifications (used for smoke sampling during 4.1-4.3 experiments)

6.7 Remote sensing aircraft

Three remote sensing aircraft participated during the NOFO 2016 Field trials (Table 6.1; Figure 6.11). A range of sensors was used in the detection of herder and oil slicks, and to document the burns.

SLAR (Side Looking Airborne Radar)

Detects oil on the sea surface by wave damping. Good range; 20 km either side of aircraft, but low resolution; about 20 m per pixel. Used operationally to locate spilled oil at sea, but limited use for experimental work

EO/IR (Electro Optical / IR also known as a FLIR (Forward Looking Infra-Red)

Camera and IR sensor with high zoom capability. Gyro-stabilised steerable turret on underside of aircraft. Can auto-track; lock onto 'target' and follow, irrespective of aircraft movements. Produces images taken at oblique angle, not straight down, vertical images

IR/UV Line scanner

Not a camera, but a line scanner. Image is built up as aircraft flies straight and level above oil. Aircraft height determines coverage and resolution. Produces two vertical images; one IR and one UV of exactly the same 'target'. Not so useful for operational oil spill response, but very useful for experimental oil spills.

Table 6.1 Participating aircrafts and sensors available

Country	Aircraft type	Registration	SLAR	EO/IR (FLIR)	IR/UV Line Scanner
Norway	King Air B350ER	LN-KYV	Yes	HDIR+HDTV+HDZ	No
The Netherlands	Dornier 224	PH-CGN	Yes	FLIR+TV	No
Finland	Dornier 224	OH-MVO	Yes	FLIR+TV	Yes

Additionally, all aircraft were equipped with hand-held HR photo-/video-cameras.

Figure 6.11 Participating remote sensing aircraft

7 TEST PLAN

7.1 Location

The HISB field experiments took place at the Frigg Field in the North Sea in mid-June 2016 as part of the NOFO Oil On Water field trial (OPV 2016).

Figure 7.1 General Location of OPV 2016 including HISB Field Experiments ((59º52'48''N; 02º03'59''E).

7.2 Layout of tests

Figure 7.1 shows the general layout of the "three plus one" HISB slicks and the three TOF slicks that were included in the experimental plan. The TOF releases were long, narrow slicks with the oil discharged as the *KV Sortland* (the ship releasing all the slicks) moved slowly forward. The HISB releases were intended to be "point source" releases with the *KV Sortland* held as stationary as possible with respect to the surface currents. In order to minimize the possibility of prop-wash or thruster-wash affecting the HISB slicks attempts were made to ensure the oil was pumped with the release hose streaming to the side of the vessel rather than astern.

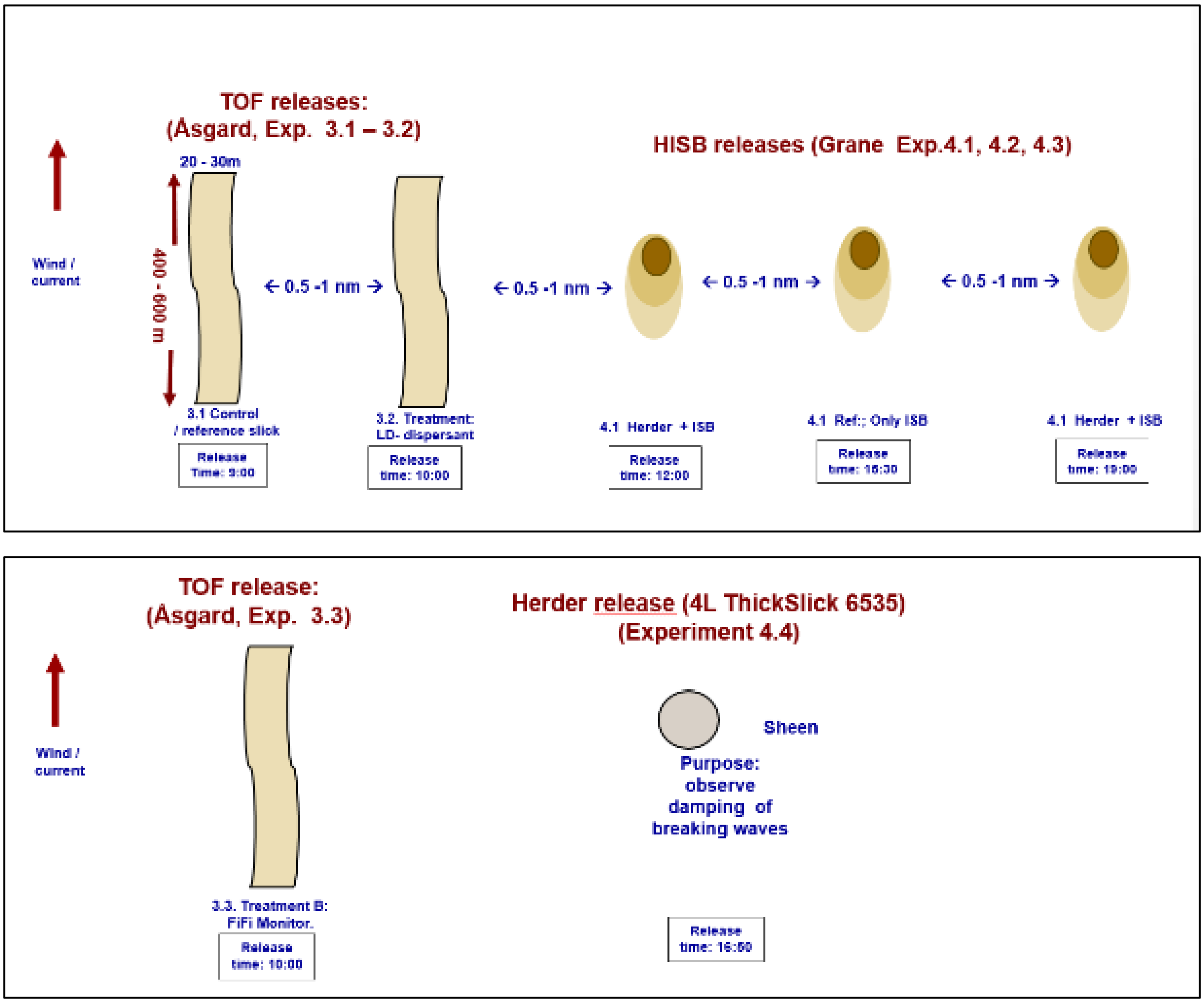


Figure 7.1 Schematics of the TOF (experiment 3) and the HISB releases (experiment 4). A: releases Day 1 (non-breaking wave conditions)..B: releases day 2, under breaking wave conditions

8 FIELD EXPERIMENTS

8.1 Test chronology

The weather conditions on Day 1 (June 14th) was calm (no breaking waves, < 5 m/s wind, and significant wave-height: 0.5- 1.2 m). The three experiments with release of oil were performed Day 1.

Total 16 m^3 of oil was released during the following three HISB experiments:

Day 1: (Tuesday 14th):

Experiment 4.1.:	6 m^3 Grane Blend crude oil, use of 4.9 L herder, Ignited.
13:20 – 14:40	
Experiment 4.2.:	6 m^3 Grane Blend crude oil, Ignited without herding.
15:38 – 17:15	Non-ignited area treated with dispersant (1.6 m^3 Dasic NS).
Experiment 4.3.:	4 m^3 Grane Blend crude oil, use of 6.4 L herder, Ignited.
19:05 – 20:15	Non-ignited area treated with dispersant (0.6 m^3 Dasic NS).

Day 2: (Tuesday 14th):

Experiment 4.4.: 16:46 – 18:00	Release of 5.0 L Herder alone (ThickSlick 6535) under breaking wave conditions.

Total use of Herder: 16.3 Litres. Total use of dispersant: 2.2 m^3 Dasic NS on non-ignited portions of the slick. Samples of surface oil and of the burned residue were collected for physico-chemical characterization.

Additionally, there was extensive daylight surveillance from three participating remote sensing aircrafts (from Norway, Finland and Belgium) and more than two effective hours with HD -video monitoring from drones (see selected images under the different experiments).

8.2 Experiment 1 (HISB 4.1: Herd and burn)

A summary of the timing of events in Experiment 1 is presented in Table 8.1. The timings are expressed as LT (Local Time) as used by the ships and boats and UTC (Coordinated Universal Time) as used by the aircraft and ET (Elapsed Time) of the experiment where the first ignition is taken as time zero.

Table 8.1 Timeline summary Experiment 1

Experiment 1 (HISB 4.1)	LT (Local time) (UTC+2:00)	UTC	ET (Elapsed Time)
Smoke signal	13:20	11:20	-0:54
Oil release start	13:21	11:21	-0:53
Oil release end	13:23	11:23	-0:51
AIS buoy deployment	13:23	11:23	-0:51

Herder application start	13:53	11:53	-0:31
Herder application end	14:00	12:00	-0:14
Initial burn	14:14	12:14	0:00
2nd burn begins	14:24	12:24	0:10
Initial burn ends	14:28	12:28	0:14
2nd burn ends	14:29	12:29	0:15
3rd burn begins	14:32	12:32	0:18
3rd burn ends	14:37	12:37	0:23
Residue collection	14:40	12:40	0:26

Weather conditions for Experiment 1 on June 14th were calm: 3-4 m/s wind from NNE and no breaking waves.

Discharge of oil

A smoke signal was released at 13:20 LT (11:20 UTC) to confirm wind direction and provide guidance for craft on the water and in the air. Six cubic metres of Grane Blend crude oil was released onto the sea surface from KV Sortland at 13:21 to 13:23 LT, over a distance of 50 to 80 metres as a long narrow slick. An Automatic Identification System (AIS) buoy was released to assist tracking the slick.

Spreading and herding of HISB 4.1 slick

Approximately 30 minutes later at 13:53 LT the MOB boats had moved into position and started the application of herder. 4.9 litres of herder was applied using a garden sprayer from a MOB boat around the perimeter of the slick.

Due to various operational issues, it was not possible to obtain aerial images of the slick prior to herding. Figure 8.1 was taken just after herding had been completed.

Figure 8.1 Photograph of HISB 4.1 slick (Netherlands Coast Guard)

The herded thick oil is visible and is surrounded by a 'halo' of thin oil sheen that had been displaced by the herder. Most of the thick oil in the slick had been herded, but about 15% to 20% of the thick oil had not being herded (marked with red circle in Figure 8.1).

An IR image obtained by the Netherlands surveillance aircraft at 12:05 UTC (14:05 LT) is shown in Figure 8.2. The orientation of the slick in Figure 8.2 is the same as in Figure 8.1 and the two MOB boats are visible in the same position. The IR 'white' area is oil that is warmer than the sea surface and correlates well with the thick oil that is visible in Figure 8.1.

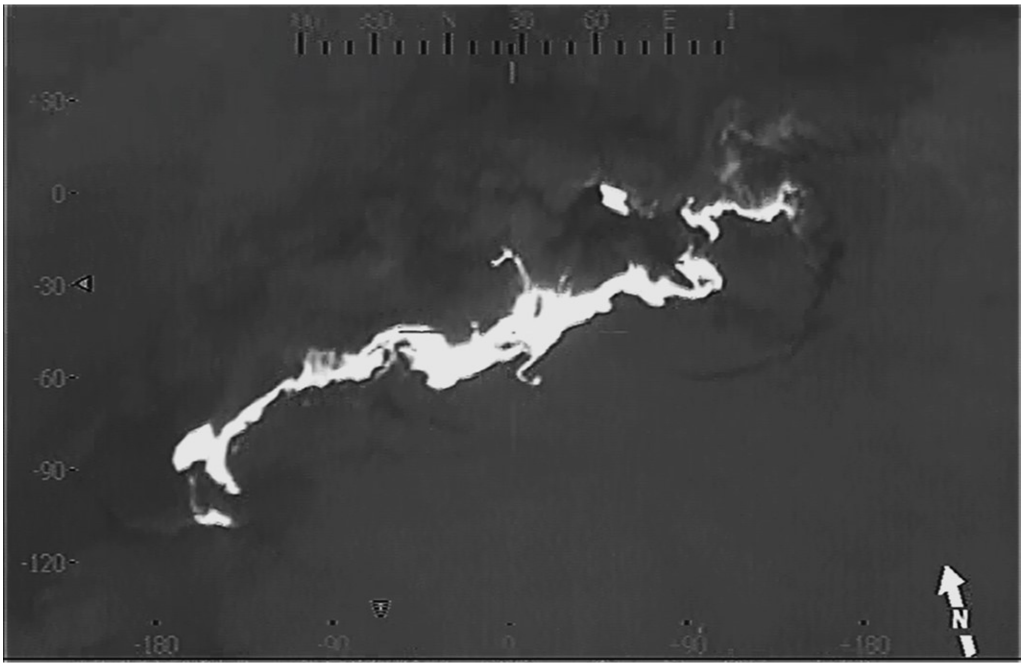


Figure 8.2 Infra-Red image of HISB 4.1 slick at 12:05 UTC (Netherlands Coast Guard)

Ignition and burning of HISB 4.1 slick

Three igniters were placed into the herded slick at 14:14 LT. Although not apparent at the time to those launching the igniters, the igniters were deployed in the downwind portion of the slick, which is not optimal for flame spreading and effective burning. By 00:45 ET the areas of the ignited oil increased to over 1 m^2 (see Figure 8.3).

Figure 8.3 HISB 4.1 slick 45 seconds after ignition

The flames continued to build and an intense burn started 1 minute 20 seconds after ignition (see Figure 8.4).

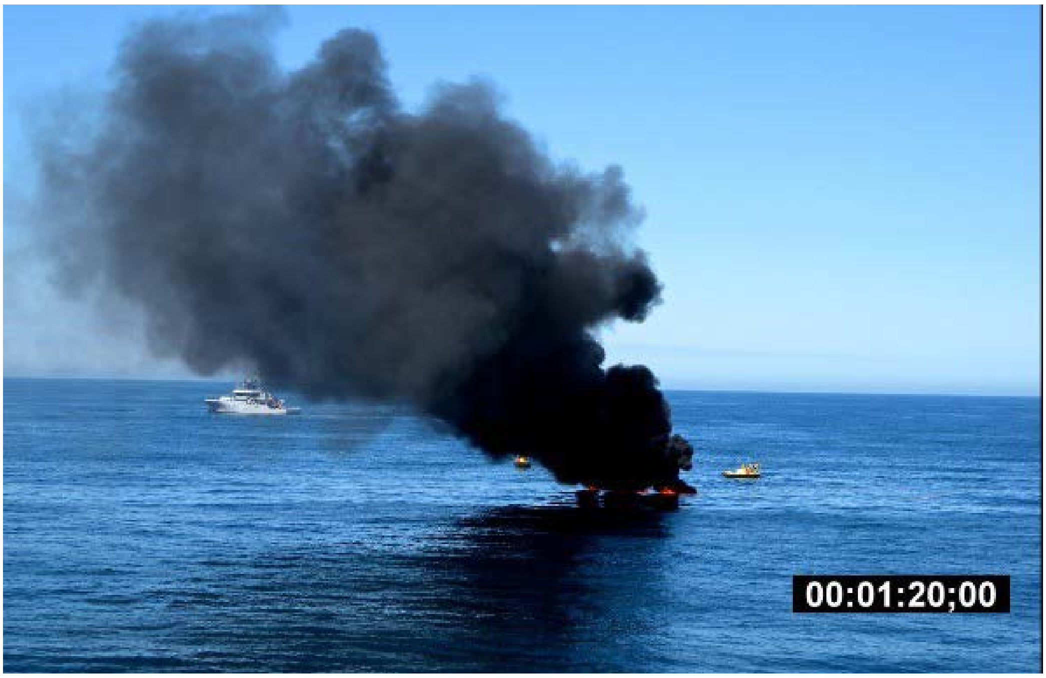


Figure 8.4 HISB 4.1 slick 1 minute 20 seconds after ignition

By 3 minutes after ignition the burn had grown in both size and intensity (see Figure 8.5). An aerial view of the initial burn (Figure 8.6) shows that some patches of oil had become separated from the main slick and had not been ignited.

Figure 8.5 HISB 4.1 slick 3 minutes after ignition

Figure 8.6 Aerial view of HISB 4.1 slick initial burn

Figure 8.7 shows a second discrete plume of smoke representing a second burn that started after the 10 minute ET.

Figure 8.7 HISB 4.1 slick 11 minutes after initial ignition

The two burns continued in the same area of the main slick. The separated areas of oil were not burned (Figure 8.8).

Figure 8.8 Aerial view of two burns in HISB 4.1 slick

The initial burn went out 14 minutes after ignition. The second burn was ignited 10 minutes after the initial burn and continued for 5 minutes. A third burn was ignited 18 minutes after the initial burn and this is shown two minutes after ignition in Figure 8.9.

Figure 8.9 HISB 4.1 slick 20 minutes after initial ignition and 2 minutes after third ignition

This third and final burn went out after 5 minutes of burning.

Recovery of burn residue

After the three burns the HISB 4.1 consisted of areas of unburned oil and burn residue (Figure 8.10).

Figure 8.10 HISB 4.1 slick after burning

A boom was deployed to collect the burn residue (Figure 8.11). The experience of using booms for containment and recovery of burn residue proved very difficult as the residue was very viscous and floated extremely heavily in the water. Even when it was possible to confine some of the burn residue, only very small amounts were actually recovered (Figure 8.12).

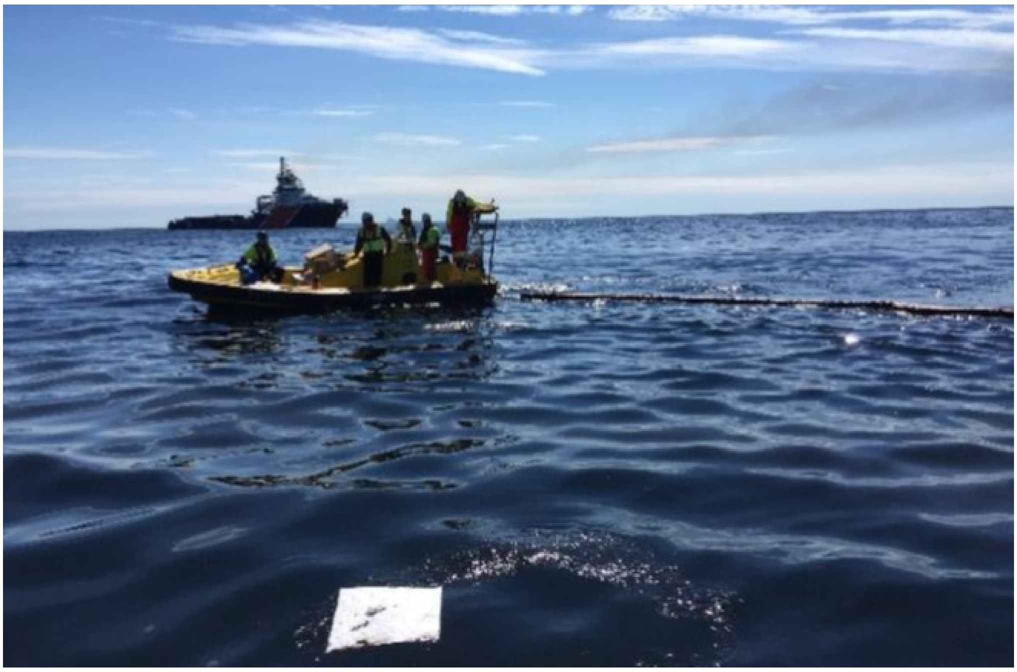


Figure 8.11 Deployment of boom for burn residue collection

Figure 8.12 Burn residue from HISB 4.1

8.3 Experiment 2 (HISB 4.2: Monitor and burn, reference slick)

A summary of the timing of events in Experiment 2 is presented in Table 8.2. The timings are expressed as LT (Local Time) as used by the ships and boats and UTC (Coordinated Universal Time) as used by the aircraft and ET (Elapsed Time) of the experiment where the first ignition is taken as time zero.

Weather conditions for Experiment 2 were also calm: 3-4 m/s wind from NNE, and no breaking waves. This test was the designated reference slick which did not have a herder component to control the spreading of the slick.

Discharge of oil

Six cubic metres of Grane Blend crude oil was released onto the sea surface from KV Sortland at 15:40 to 15:43 LT. The oil was released over approximately 50 metres. The wind at 3 - 4 m/s was from the NNE and the sea was calm with no breaking waves.

Spreading of the HISB 4.2 slick

In the very calm conditions the slick did not drift and remained compact (a maximum of 90 metres long and 35 metres wide) with some sheen around it (Figure 8.13).

The sheen has a thickness ranging from 0.4 to 0.30 microns (Silver sheen) up to 5 microns (Rainbow sheen) and therefore represents a miniscule proportion of the oil volume; over 97% of the volume of oil is present in the thick oil area.

It was very difficult to see and locate the areas of thick oil from the MOB boat. The thick oil area in the HISB 4.2 was cut into several separate pieces by the MOB boat(s) inadvertently traversing through the thick oil area. Visual observation from the MOB boat suggested that the gaps in the thick oil caused by the boat tracks closed up.

IR images from the surveillance aircraft showed that only thin oil flowed into these gaps, leaving strips of thin oil separating areas of thick oil. Figure 8.14 is a still taken from the HDIR video of the Norwegian surveillance aircraft. The IR convention used in this image is "White is Hot" and the white areas in the image show the areas of thick oil that were warmer than the surrounding sea.

Table 8.2 Timeline summary Experiment 2

Experiment 2HISB 4.2	LT (Local time) (UTC+2:00)	UTC	ET (Elapsed time) (hh:mm)
Smoke signal	15:38	13:38	-0:56
Oil release start	15:40	13:40	-0:54
Oil release end	15:43	13:43	-0:51
AIS buoy deployment	15:43	13:43	-0:51
Initial burn	16:34	14:34	0:00
2nd burn begins	16:35	14:35	0:01
Initial burn ends	16:37	14:37	0:03
3rd burn attempt	16:38	14:38	0:04
2nd burn ends	16:40	14:40	0:06
4th burn attempt	16:41	14:41	0:07
Return to Strilborg for igniters	16:44	14:44	0:10
Return to test area	16:55	14:55	0:21
5th burn attempt	16:56	14:56	0:22
6th burn attempt	16:57	14:57	0:23
7th burn attempt, ignition and 3rd burn begins	16:58	14:58	0:24
8th burn attempt	17:02	15:02	0:28
3rd burn ends	17:06	15:06	0:32
Dispersant spraying on unburnt area of oil start	17:25	15:25	
Dispersant spraying on unburnt area of oil end	17:45	15:45	

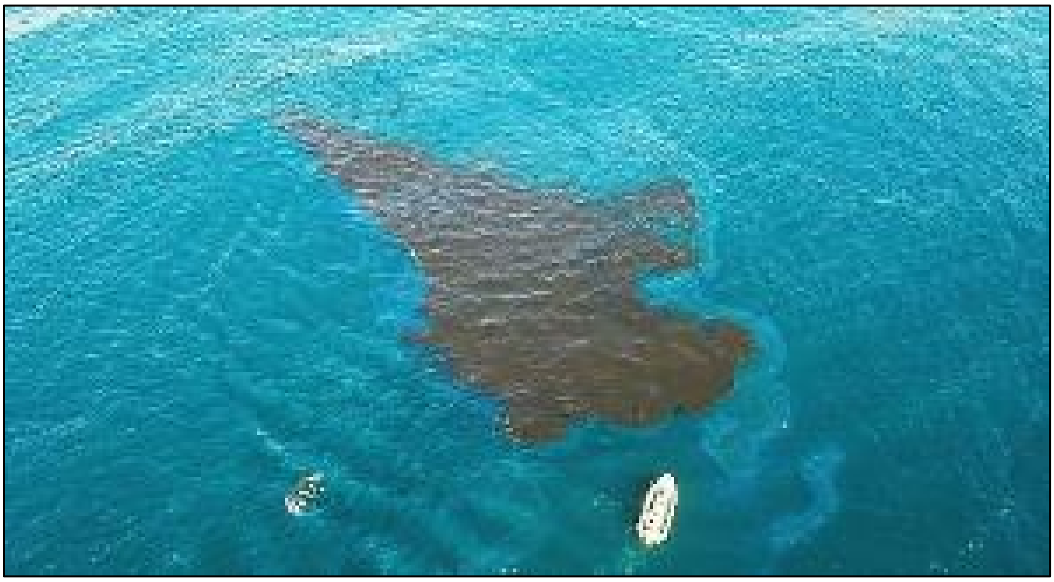


Figure 8.13 HISB 4.2 slick with compact area of thick oil surrounded by sheen.

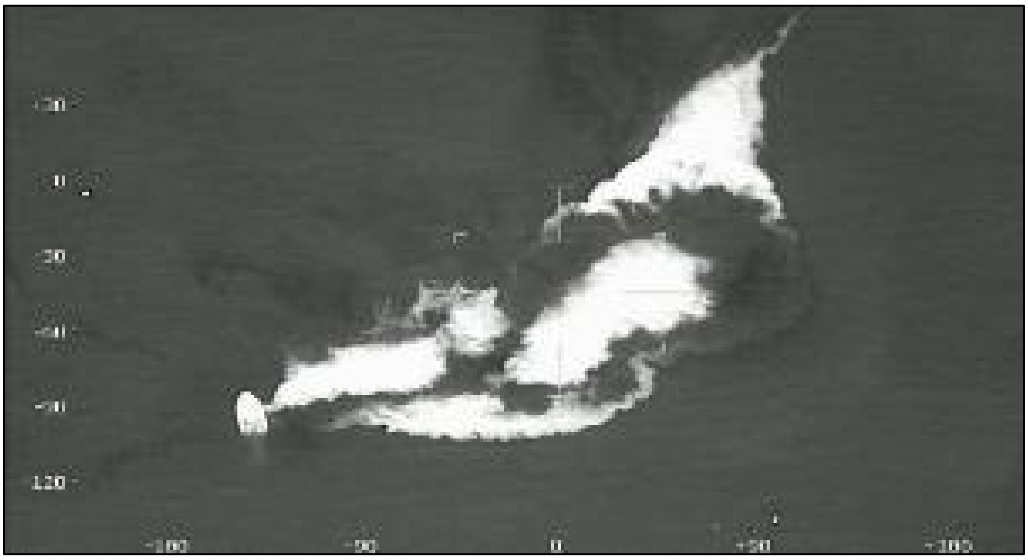


Figure 8.14 IR image of HISB 4.2 slick just as igniters were deployed 14:34 UTC (16:34 LT).

Ignition and burning of the HISB 4.2 slick

An igniter was deployed from the MOB boat 50 minutes after the oil had been released onto the sea surface and the oil started to burn. A second igniter was added in the generally the same area one minute later (Figure 8.15). Both of the igniters had been placed in the downwind portion of the slick, as is evident from the smoke plumes. The second burn started approximately 1 minute after the first (Figure 8.16).

Figure 8.15 Ignition of HISB 4.2 slick time 14:35 UTC (16:35 LT)

Figure 8.16 Ignition of HISB 4.2 slick - second burn begins..

The initial burn lasted for approximately 3 minutes while the second burn continued for 5 minutes (Figure 8.17). Figure 8.18 is a still from the HDIR video taken at 14:41 UTC (16:41 LT) after the second burn had ended at 16:40 LT (14:41 UTC).

Figure 8.17 Intense burn in part of HISB 4.2 slick at 14:38 LT (16:38 UTC).

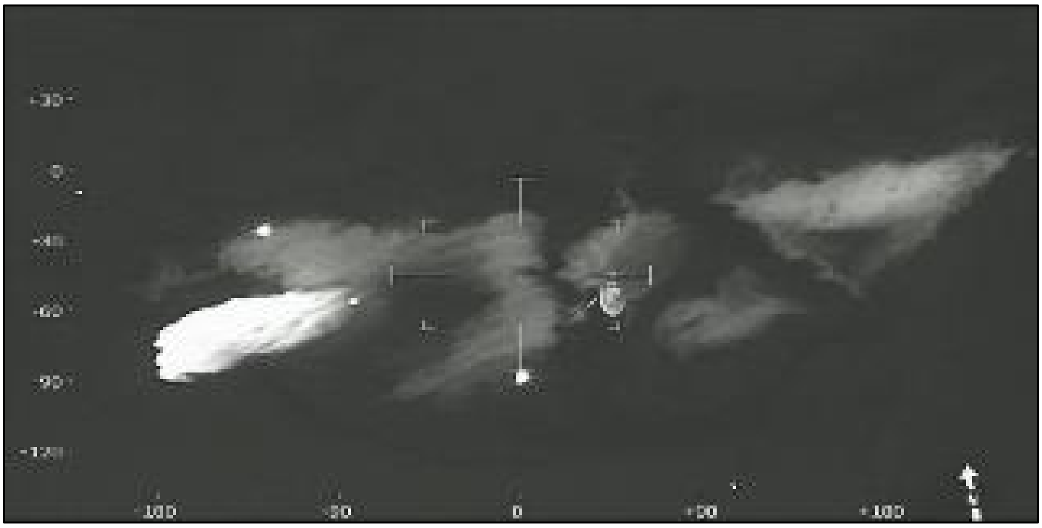


Figure 8.18 HISB 4.2 slick at 14:41 UTC (16:41 LT). Norwegian aircraft.

The area of the thick oil in the slick where the first two burns had taken place shows up as a brighter white in the image because the residue remaining after the burn is still very warm. It can be seen that the first two burns were confined to just one of the separated thick oil patches with an area of approximately 300 m^2. The three bright spots in the image are additional igniters that have been deployed, but these failed to ignite the oil.

Further attempts were made to ignite the oil, but were unsuccessful. After all igniters in the MOB boat had been used, one of the MOB boats returned to the M/V Strilborg at 16:44 LT to prepare additional igniters. This took a few minutes and the MOB boat returned with these igniters to the HISB 4.2 slick at 16:55 LT. The freshly-prepared igniters were used in renewed attempts at ignition. Ignition was achieved at 16:58 LT (Figure 8.19).

The oil in the HISB 4.2 slick had been on the water for 75 minutes by the time of ignition of the third burn. The third burn continued through for 8 minutes (Figure 8.20) and ended at 17:06 LT.

Figure 8.19 HISB 4.2 slick 90 seconds minutes after third ignition.

Figure 8.20 HISB 4.2 slick during third burn (B).

As is evident from the smoke plume in Figures 8.19 and 8.20, the third burn had been at the 'opposite end' (the upwind portion of the slick) of the HISB 4.2 slick from the first two burns. The burn was in the triangular section of the slick on the right-hand side of the IR image in Figure 8.18, and to the top of the IR image in Figure 8.14.

This triangular area had a total area of approximately 400 m^2, but transits by the MOB boats during ignition attempts had further sub-divided this area into smaller sections. No IR images were obtained shortly after the third burn, so it is not possible to accurately determine the area of the slick that had been subject to burning during the third burn.

8.4 Experiment 3 (HISB 4.3: Herd and burn)

Changing weather conditions with more severe winds being forecast the following day let to changes in the original schedule culminating with Experiment 3 taking place late in the day on June 14th.

A summary of the timing of events in Experiment 3 is presented in Table 8.3. The timings are expressed as LT (Local Time) as used by the ships and boats and UTC (Coordinated Universal Time) as used by the aircraft and ET (Elapsed Time) of the experiment where the first ignition is taken as time zero.

The wind had increased to 5 m/s from NNE and there were slightly rougher seas, with occasional breaking waves.

Discharge of oil

A smoke signal was released at 19:05LT (17:05 UTC) to confirm wind direction and provide some guidance for craft on the water and in the air.

Because 2 m^3 of oil would always be remaining in the tank after pumping out (see 6.2) and we had only 18 m^3 of oil totally available, 4 m^3 of Grane Blend crude oil was released onto the sea surface from KV Sortland at 19:08 to 19:11 LT. This started as a compact area of thick oil. As the slick drifted with the wind, it spread out to form a larger slick with thin and thick oil areas (see Figure 8.21).

Table 8.3 Timeline summary Experiment 3

Experiment 3 (HISB 4.3)	LT (Local time) (UTC+2:00	UTC	ET (Elapsed time) (hh:mm)
Smoke signal	19:05	17:05	-0:57
Oil release start	19:08	17:08	-0:54
Oil release end	19:11	17:11	-0:51
Herder application start	19:37	17:37	-0:24
Herder application end	19:45	17:45	-0:16
Initial burn attempt	19:52	17:52	-0:09
2nd burn attempt and ignition	20:01	18:01	0:00
3rd burn attempt	20:01	18:01	0:00
4th burn attempt	20:02	18:02	0:01
Burn separation to 2 burns	20:03	18:03	0:02
5th burn attempt	20:08	18:08	0:07
End of burn	20:09	18:09	0:08
Dispersant spraying of unburnt oil start	20:25	18:25	
Dispersant spraying of unburnt oil end	20:35	18:35	

Spreading of the HISB 4.3 slick

The winds were noticeably higher for this experiment compared to those experiments conducted earlier in the day. Cloud coverage obscured the sun making visibility of the oil slick extremely difficult from the vantage point of the MOB boats. The Securus IR on the M/V Strilborg had poor signal response, making remote guidance around the perimeter of the slick extremely difficult. Although only 4 m^3 of oil had been deposited, the higher wind speed started to cause the slick to cover a noticeably larger area than the 6 m^3 of oil used in the previous two experiments. This was compounded by the flushing of the 50 m hose at the end of the discharge which added a streaming band of oil to the end of the original slick (Figure 8.22).

Figure 8.21 Discharge of the HISB 4.3 slick.

Figure 8.22 HISB 4.3 slick starting to spread out 4 minutes after oil release ended

The HISB 4.3 slick drifted with the wind during the 30 minutes before herder application. The drifting with the wind caused a re-distribution of the oil within the slick; the thick oil was concentrated into the downwind side of the slick with a trail of thinner oil 'behind' the thick oil. The distribution of oil within the HISB 4.3 slick at the start of herding is illustrated in Figure 8.23.

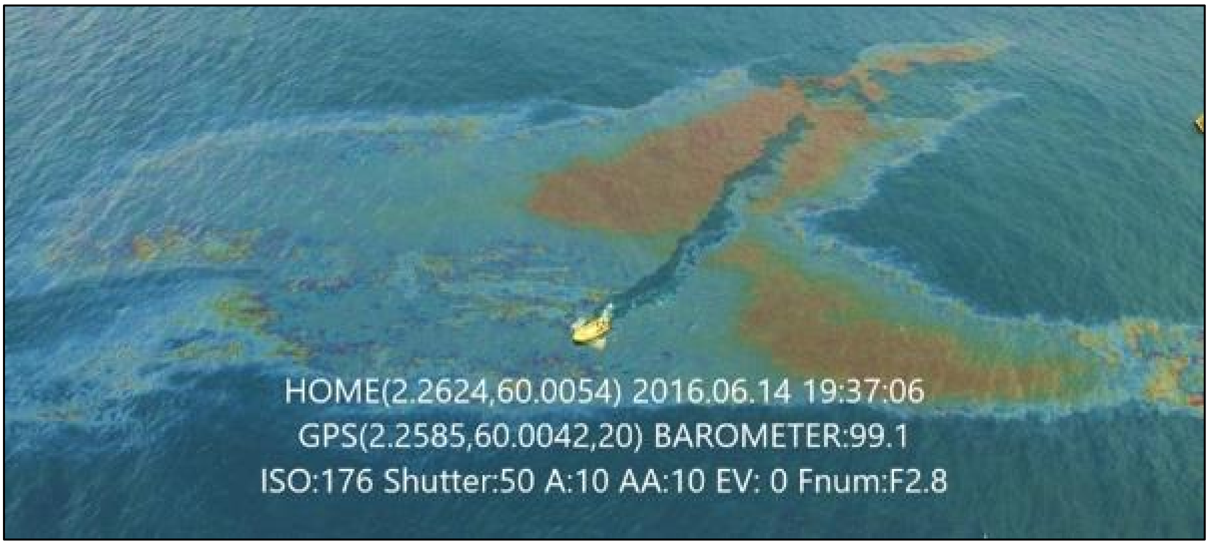


Figure 8.23 HISB 4.3 slick at the start of herding.

The most coloured area of slick in the enhanced image in Figure 8.23 is the thick oil and the areas of thinner sheens can also be seen. Image analysis was used to estimate the areas of different thickness within the HISB 4.3 slick in accordance with the BAOAC (Bonn Agreement Oil Appearance Correlation) (http://www.bonnagreement.org/). The results of this analysis are presented in Table 8.4.

Table 8.4 BAOAC analysis of HISB 4.3 slick in Figure 8.12.

BAOAC (Bonn Agreement Oil Appearance Correlation)			HISB 4.3 in Figure 8.12			
Code number	Appearance description	Layer Thickness Interval (μm)	Area (m^2)	Percentage of area (%)	Percentage of Volume (%)	
					min	max
1	Sheen	0.04 to 0.30	2,750	25	0.003	0.02
2	Rainbow	0.30 to 5.0	2,330	21	0.02	0.31
3	Metallic	5.0 to 50	2,640	24	0.35	3.47
4	DCTC	50 to 200	None evident	0	0	0
5	Continuous True Colour CTC	200 to More than 200	3,470	31	99.6	96.2
			11,200	100		

Herding of the HISB 4.3 slick

Figure 8.24 a. to h. is a sequence of still from the drone video showing the herding of the HISB 4.3 slick. It has had colour saturation increased to 200% to make the difference appearance of the areas of different oil thickness more apparent. The area of thicker oil is evident in these images as the brown colouration, but this was not visible from the boats.

The MOB boat applied herder, 6.4 litres over a 7 minutes period, around a section of the HISB 4.3 slick and the herded area included thick oil, but also some area of the thinner oil.

The events in each of the eight images are as follows:

- 19:37:01 LT (30 seconds after herder spraying began)

The MOB boat spraying herder has entered the HISB 4.3 slick from the open water and cut through a section of the thick oil and then has passed into the thinner oil (Metallic and Rainbow sheen in the BAOAC). A narrow channel of clear water in the wake of the boat has been formed by the herder application.

- 19:37:21 LT (50 seconds after herder spraying began)

The MOB boat spraying herder makes a 90° turn to the right while in the area of Rainbow sheen. The area where herder has previously been sprayed is a widening channel of clear water. The channel is wider in the thinner oil than in the thicker oil.

- 19:37:41 LT (70 seconds after herder spraying began)

The MOB boat spraying herder makes a second 90° turn to the right to form a parallel track to that on which it entered the slick. It passes through the area of thinner oil and then re-enters the thick oil. The channel of clear water created by the herder in the thinner oil is wider indicating that the thinner oil is being herded faster than the thicker oil.

- 19:38:00 LT

The MOB boat, still spraying herder, re-enters clear water outside the main body of the slick.

- 19:38:15 LT

The deposited herder on the water surface is visible as a very thin, slivery trail.

- 19:39:17 LT

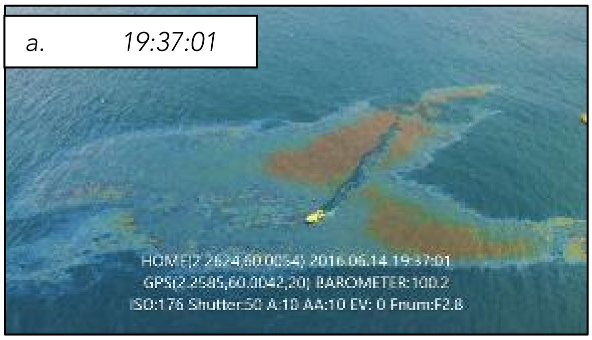
The second MOB boat enters an area of the oil outside that which has been subject to herding. The channel of clear water formed by herder application has continued to widen. The area of thinner oil that was inside the herded area has contracted to only a small area.

- 19:37:41 LT

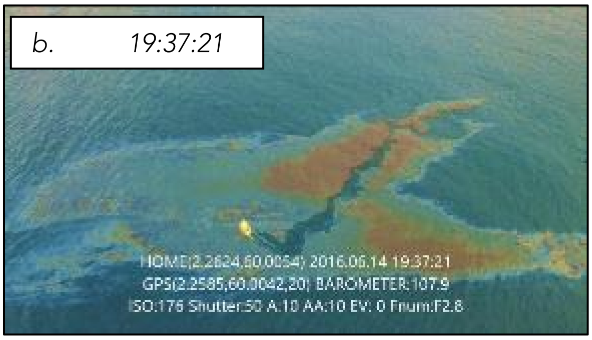
The second MOB boat enters the area of thick oil that has been herded and passes through the main section.

- 19:41:26 LT

The area of thick oil that has been herded looks granular and has broken into several fragments.



a. 19:37:01



b. 19:37:21

c. 19:37:41

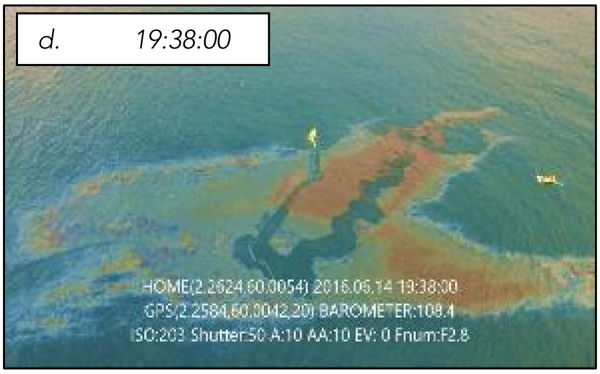
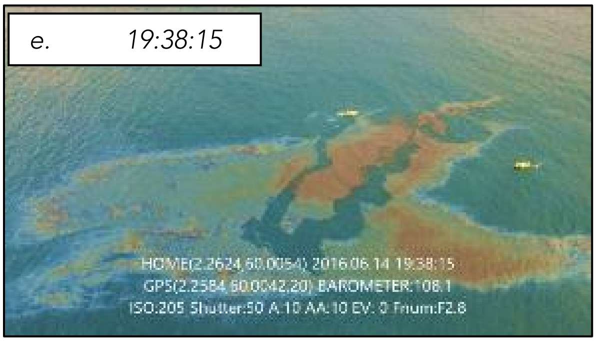
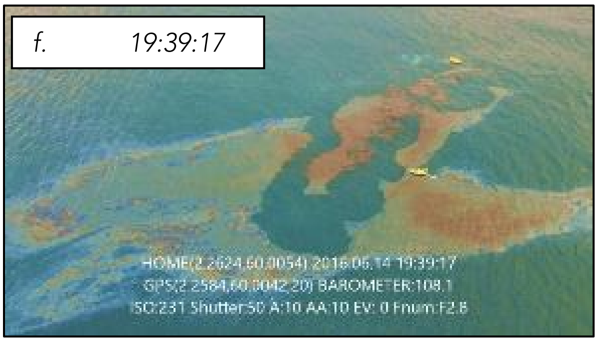
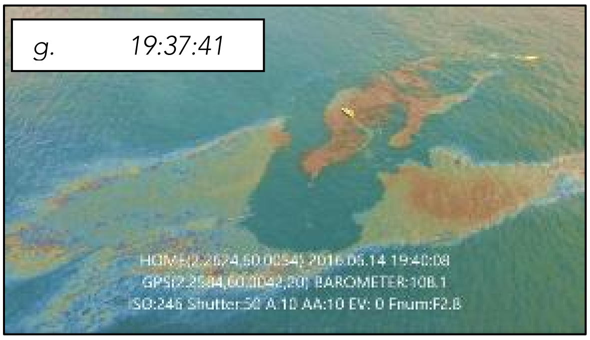
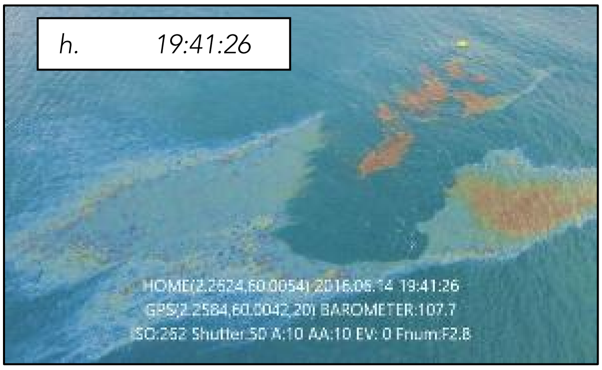


Figure 8.24 Herding of section of HISB 4.3 slick









Ignition and burning of the HISB 4.3 slick

The areas of herded oil before ignition are shown in Figure 8.25 within the red ellipse. Igniters were deployed at 19:52 LT and at the second attempt the oil was ignited at 20:01 LT (Figure 8.26).

Figure 8.25 Areas of herded oil in slick HISB 4.3 before ignition.

Figure 8.26 Ignition of the HISB 4.3 slick..

The burn accelerated and quickly intensified by about 1 minute after ignition (Figure 8.27). This intensity was maintained over the next couple of minutes. A second burn ignited close to the first (Figure 8.28).

Figure 8.27 The first burn intensified quickly (A) and the second burn starts in HISB 4.3 (B).

Figure 8.28 Second burn starts in HISB 4.3 (B).

After approximately 30 seconds the second burn increased in intensity and approximately one minute after starting, the second burn was fully developed (Figure 8.29). The second burn continued for another 6-7 minutes (Figure 8.30).

Figure 8.29 Second burn fully developed in HISB 4.3 (A) and extinguished after eight minutes (B).

Figure 8.30 Second burn fully developed in HISB 4.3 (A) and extinguished after eight minutes (B).

8.5 Experiment 4 (HISB 4.4: herder only)

The fourth experiment conducted on June 15th was the release of 5 L of herder into occasional breaking waves. The wind speed was 8 m/s from NNE.

A smoke signal was deployed at 16:46 LT (14:46 UTC) to provide confirmation of wind direction and provide guidance for the craft in the water and in the air. Five litres of herder was deposited over the side of the MOB at 16:47 (Figure 8.31).

Figure 8.31 Herder poured on to the sea surface (Finnish Border Guard / SYKE)

The MOB slowly moved away to clear the spreading herder monolayer, then circled around to take up a position downwind of the smoke signal, angled towards the expanding herder monolayer. The area of herder on the sea surface slowly expanded, being most visible in the sun glitter (see Figure 8.32).

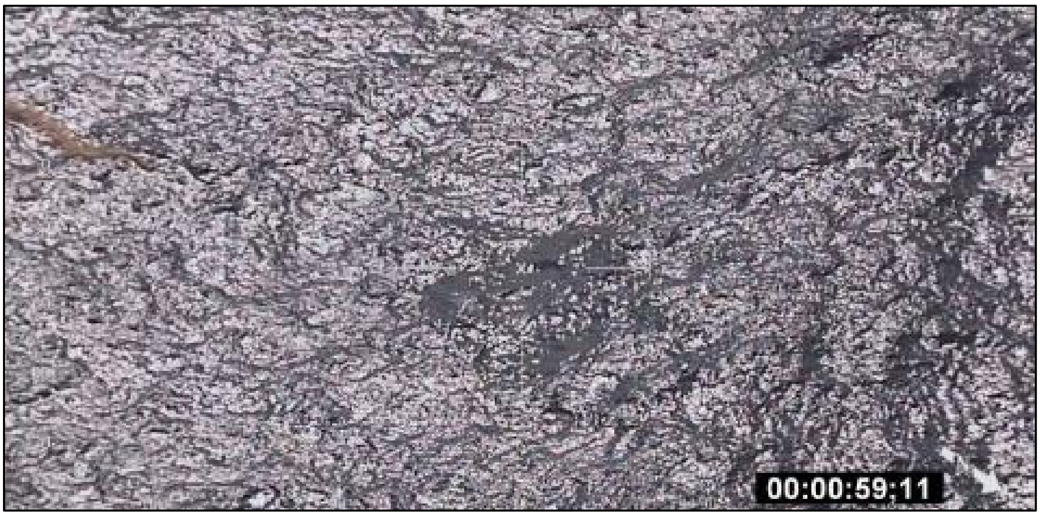


Figure 8.32 Herder one minute after deposition (Finnish Border Guard / SYKE)

After 8 ½ minutes on the water the herder was visible as a comparatively calm area identifiable in the centre of Figure 8.33 (note white “dot” slightly above centre, at the 11 o’clock position of the reticule is the MOB vessel, with the M/V Strilborg at the upper edge of the video frame grab).

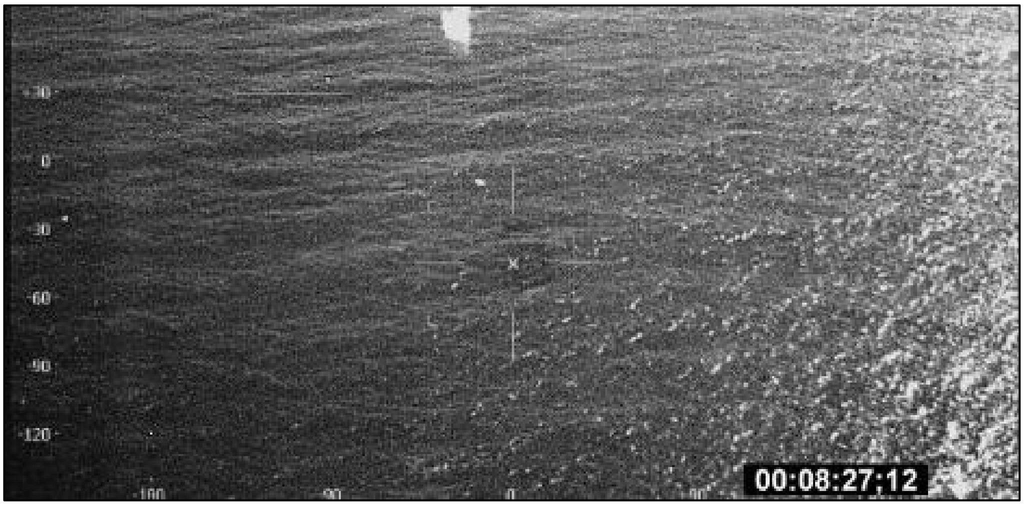


Figure 8.33 Herder after 8 ½ minutes on the sea surface (Finnish Border Guard / SYKE)

As time progressed, the herder area continued to expand. Figure 8.34 shows the herder in the sun glitter 12$^{1}/_{2}$ minutes after it was placed on the sea.

Figure 8.34 Herder after 12 ½ minutes on the sea surface (Finnish Border Guard / SYKE)

As well as being visible in the sun glitter, the herder was also evident in IR images, showing as being slightly cooler than the surrounding sea surface as shown in Figure 8.35.

Figure 8.35 IR image of herder after 31 minutes on the sea surface (Finnish Border Guard / SYKE)

The herder was visible or detectable in IR from the aircraft for nearly an hour after it has been placed on the sea surface. The slightly darker area indicate that it is cooler than the surrounding sea surface water. That might be due to evaporation of the 35 % 2-ethyl butanol solvent from the herder or the emissivity (effectiveness in emitting energy as thermal radiation). The area grew steadily during this time and is shown in Table 8.5.

Table 8.5 Area of 5 litres of herder on sea surface with time

Time on sea surface (min)	Width (m)	Length (m)	Area (m^2)
0	1	1	1

5	40	100	4,000
10	45	100	4,500
11	50	100	5,000
18	50	240	12,000
25	50	300	15,000
40	70	400	28,000
75	not detected	not detected	

8.6 Smoke plume sampling

Air measurements were taken during each of the three ISBs. Burn durations of the oil slicks were anticipated to last approximately 10 minutes; however, burns occurred during windows of up to 30 minutes during a test run, enabling a wider opportunity to proceed with the remote sampling efforts. Air measurements were taken at three locations for PM2.5-particles, total particle/dust, and for PAHs in the "total" particle/dust fraction and in the vapour phase. A drone (Figure 8.36) was used for sampling in the smoke plume. Details of the plume sampling can be found in Appendix F.

Figure 8.36 Take-off from MS Strilborg for sampling drone with SidePak and sampling train for sampling of soot, PAH's and BTEX's in the smoke plume

9 RESULTS AND DISCUSSION

The spreading of oil and the resultant thickness of the oil layer formed on the sea is an essential element of the consideration of ISB.

The main approach in evaluation of the results has been to analyse the amount of oil (as an area or derived volume) that was present as oil thicker than 1 mm (regarded as a minimum thickness for successful ignition). The approach includes analysis of a large amount of pictures and videos, combined with a few oil thickness measurements, and depends upon:

- How much oil was released and how the oil spread out on the sea surface into areas of thick and thin oil.
- How much of the thick oil was then surrounded by herder.
- What happened to the area of the thick oil after herding.
- How much oil (area, thickness and amount) was available for, or exposed to, ignition.

This approach is referred to as "Analysis of Spreading and Herding for Burning" (ASHB).

Combustion of oil is a vapour phase phenomenon; hydrocarbons within the oil have to be in the vapour phase to burn. The key oil slick parameter that defines whether or not the oil will burn is slick thickness; if the oil is thick enough it acts as insulation and keeps the burning slick surface at a high temperature for vaporisation by reducing heat loss to the underlying water. As the slick thins, increasingly more heat passes through it. Eventually, when the oil layer is about 1 mm thick, enough heat is transferred through the slick to causes the surface oil temperature to drop below its fire point, at which time burning stops quite suddenly. A 'rule of thumb' about ISB is therefore that a minimum average oil layer thickness of greater than 1 mm is required for burning to be sustained after ignition of fresh, unemulsified crude (Buist et al. 2014).

The oil used in these experiments was a very lightly weathered 'fresh' crude oil and therefore would be likely to burn, but only if the oil layer thickness was greater than 1 mm. The three HISB experiments at sea were all conducted on the same day, June 14th 2016, over a period of 7 hours. The same Grane Blend crude oil was used for all the experiments; 6 m^3 for HISB 4.1 and 4.2 and 4 m^3 for HISB 4.3. The oil release conditions were nominally the same, although there was some variation. The prevailing wind speed was low, but increased slightly during the experimental period.

Despite these similarities, there were marked differences in the behaviour of the oil when it had been released onto the sea. The three aspects of each experiment were:

A. Spreading of the oil
B. Herding of the oil
C. Ignition and burning of oil

Each of these aspects is considered separately in the following discussion.

9.1 Spreading of oil

a. <u>HISB 4.1</u>

The 6 m^3 of oil in the HISB 4.1 slick were released onto the sea as a narrow strip about 50 to 80 metres long.

As noted earlier, no aerial images exist of the HISB 4.1 slick before herding, so no accurate estimates of the slick area (and therefore thick oil thickness) can be made. However, the image obtained from the Netherlands surveillance aircraft after herding was completed (Figure 8.1) indicates approximately the area that the oil had previously spread before herding. The same image is reproduced as Figure 9.1 where the probable location of herder application is shown as a broken yellow line.

The spreading pressure exerted by the herder would have contracted the thick oil 'inwards' (effect shown as yellow arrows) and the thin sheen 'outwards' (effect shown as red arrows).

This indicates that the area of the oil before herding was probably around 4,250 m^2 (with a range of 3,500 m^2 to 5,000 m^2) and probably had an average oil layer thickness of approximately 1.1 mm to 1.6 mm before herding. In the absence of relevant images no better oil area estimate can be made.

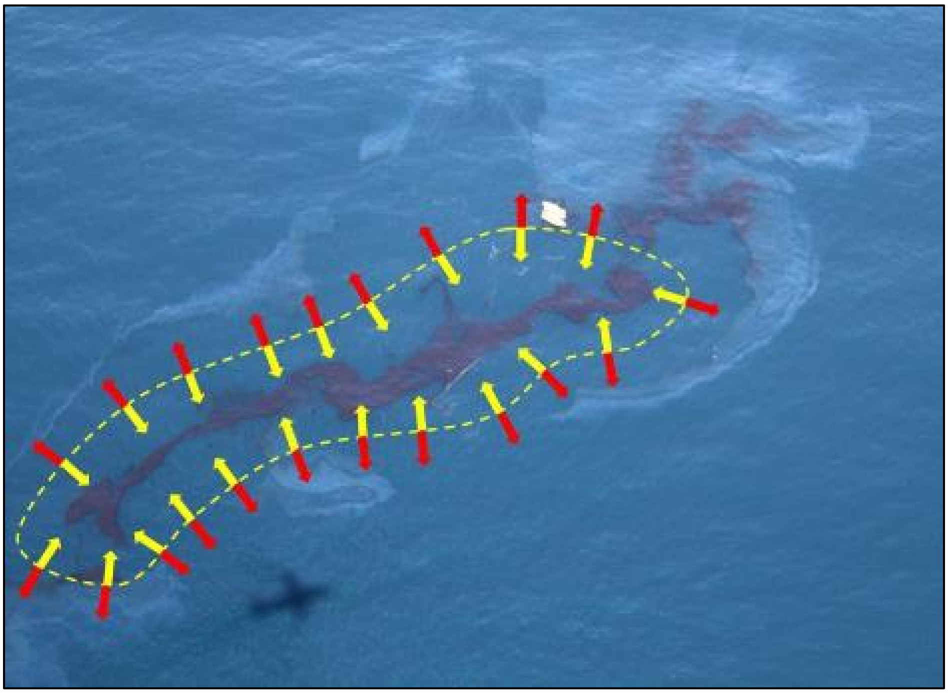


Figure 9.1 Probable area of oil HISB 4.1 slick before herding

b. HISB 4.2

The 6 m^3 of oil released to form the HISB 4.2 slick was released over a shorter distance of 50 metres and formed a very compact slick with a maximum length of about 90 metres long and a maximum width of 35 metres. In the very light wind, the oil spread only very slowly and before ignition the thick oil had an area of 2,150 m^2 (range of 2,000 m^2 to 2,350 m^2).

Allowing for a nominal 5% volume loss due to evaporation of the most volatile components, the average oil layer thickness was 2.4 mm to 2.9 mm. This is in broad agreement with measurement made at several locations in the slick by pad sampling (Figure 9.2).

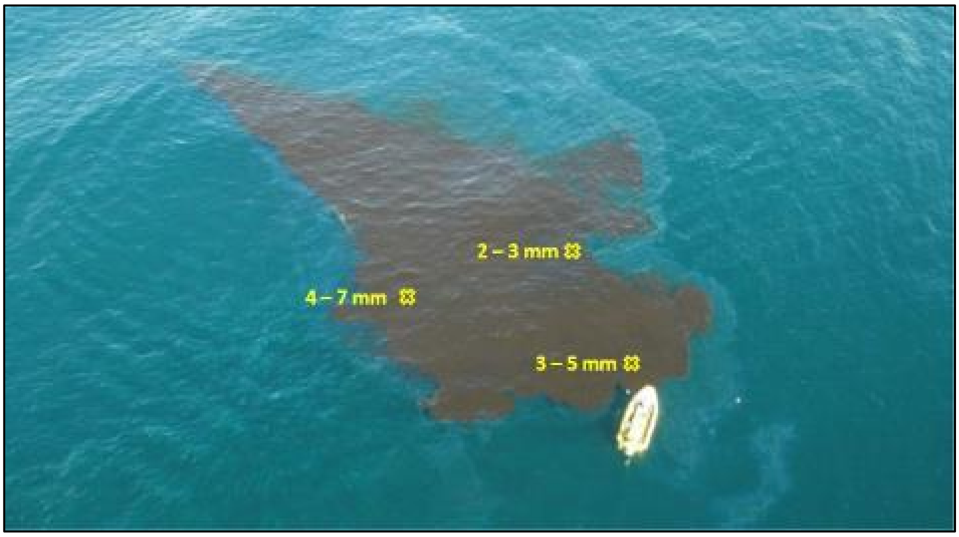


Figure 9.2 Ground-truth oil slick thickness measurements in HISB 4.2

HISB 4.3

The 4 m^3 of oil released to form the HISB 4.3 slick was initially released as a compact slick, but with a long trail as a result of the discharge hose being flushed with water. The oil slick drifted in the strengthening wind. This caused the slick to increase in total area by:

i. The formation of a trailing area of much thinner oil (silvery / grey sheen, Rainbow sheen and Metallic appearance oil). This was created by temporary dispersion of some oil that re-surfaced 'behind' the main slick of thicker oil; and

ii. The spreading out of the thicker oil leading to a larger, thinner layer.

The different areas of oil thickness, categorised according to the BAOAC, in HISB 4.3 at the start of herding are shown in figure 9.3. (Only the areas affected by the herding operation are annotated).

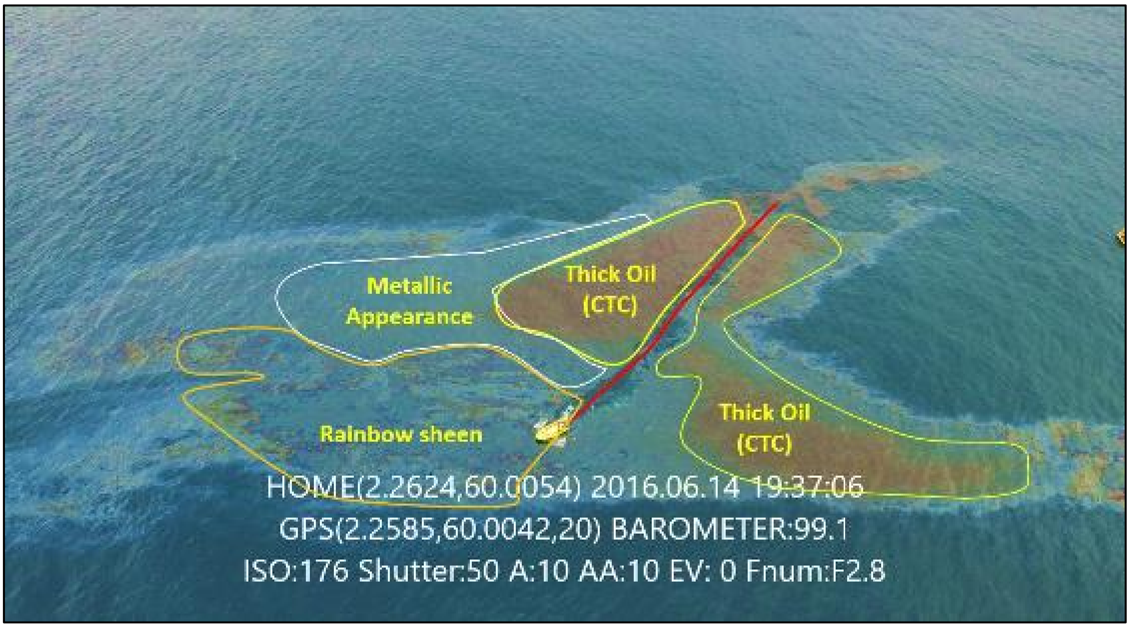


Figure 9.3 Distribution of oil BAOAC thickness areas within HISB 4.3 at start of herding

The total area of the slick was approximately 11,200 m^2. With an estimated accuracy of $\pm$15% the total slick area was between 9,500 m^2 and 12,900 m^2.

The area of the thick (BAOAC category Continuous True Colour - CTC) oil was around 3,500 m^2, representing 30% of the total slick area. The thick oil area of 3,500 m^2 in the HISB 4.3 slick contained at least 96% of the total oil volume and had an average thickness of approximately 1.1 mm.

Summary of oil spreading

Figure 9.4 summarizes the estimated areas of thick oil from the 3 experiments: before herding, areas of oil subjected to herding, areas after herding and areas of oil subjected to burn. Figure 9.5 summarizes the estimated average thickness of thick oil in the 3 experiments, before and after herding.

Although no herder was applied to the HISB 4.2 slick, it had a higher average oil thickness of 2.4 to 2.9 mm than the HISB 4.1 slick (1.1 to 1.6 mm) and HISB 4.3 slick (1.1 mm) before they were herded. This is because the HISB 4.2 slick was released as a generally compact slick and did not drift in the very low prevailing wind speed. HISB 4.1 had been released as a long, narrow band of oil and HISB 4.3 drifted with the (increased) wind. Both of these factors produced thinner layers of oil in these slicks.

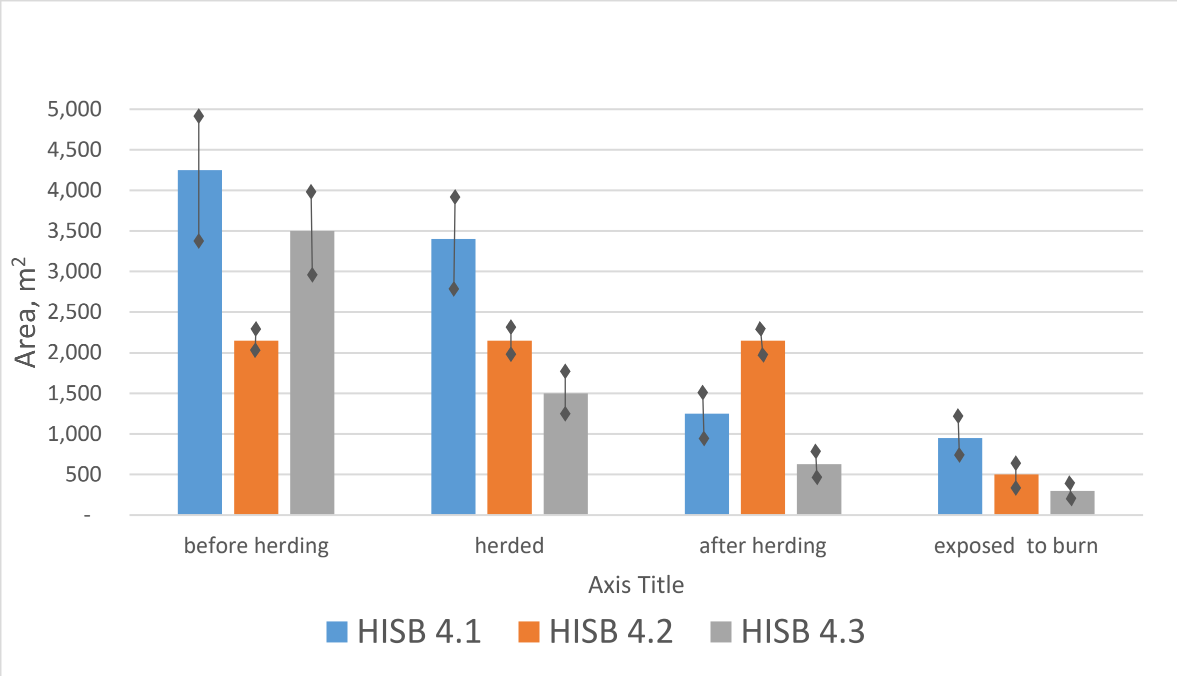


Figure 9.4 Estimated areas of thick oil for the different experiments from before herding through to areas exposed for burn.

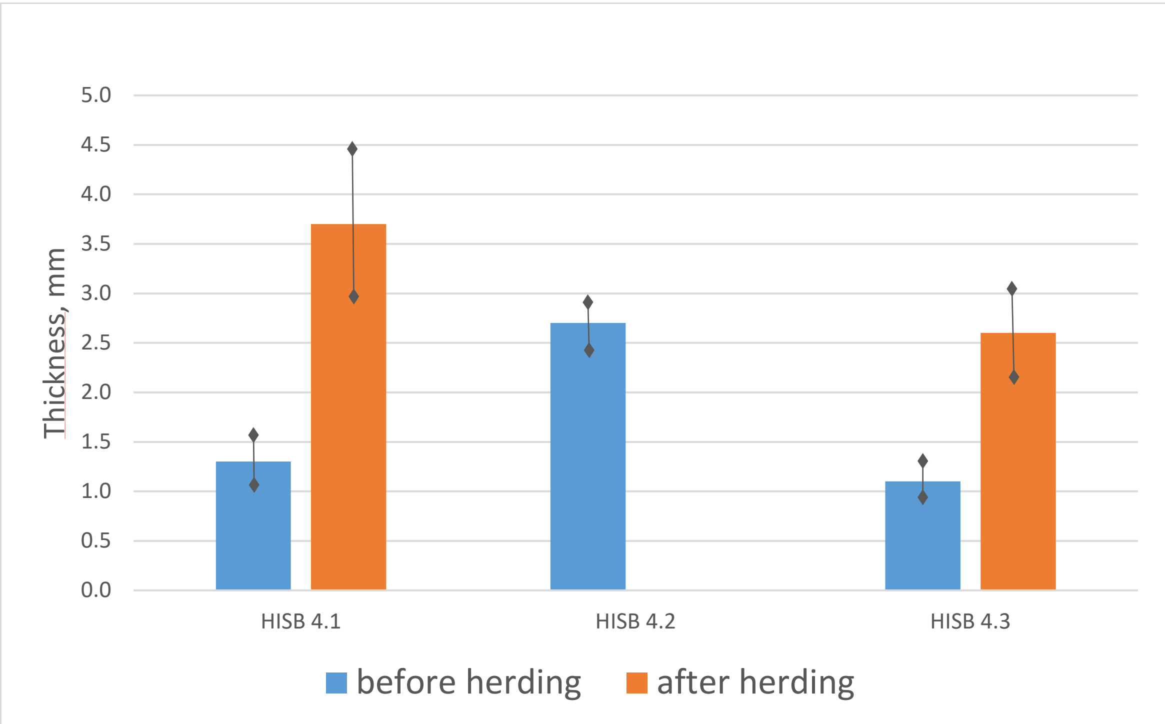


Figure 9.5 Estimated average thickness of thick oil for the different experiments, before and after herding. HISB 4.2 was not herded.

9.2 Herding of oil

a. HISB 4.1

Approximately 80% of the thick oil area in the HISB 4.1 slick was herded into a linear, but coherent, slick.

The area of the oil after herding was estimated to be 1,250 m^2 with an error of +20% to give a range of 1,000 m^2 to 1,500 m^2. With a total of 6 m^3 of oil released and allowing for a nominal 5% volume loss due to evaporation of the most volatile components, the average oil layer thickness in the herded area was approximately 3.0 mm to 4.6 mm.

b. HISB 4.2

No herder was applied to the HISB 4.2 slick and the average oil thickness before ignition was 2.4 mm to 2.9 mm. Repeated transits by MOB boats through the thick oil area in the HISB 4.2 slick had broken the thick oil into several discrete patches as indicated in the IR image (Figure 9.6) taken just as igniters were deployed.

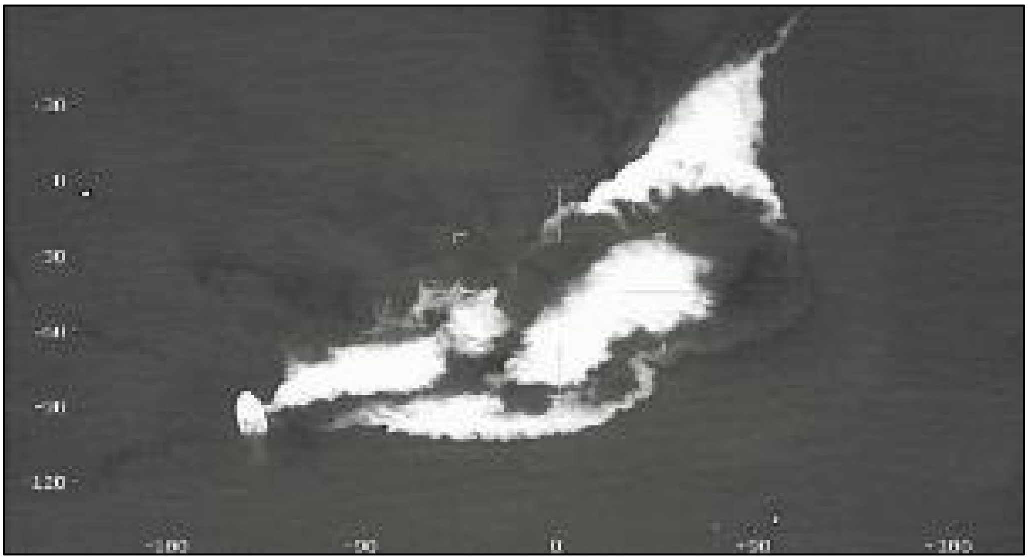


Figure 9.6 IR image of HISB 4.2 slick just as igniters were deployed.

c. HISB 4.3

The sequence of events in herding the HISB 4.3 slick is shown in detail in Figure 8.13 a. to h.

The area of the HISB 4.3 slick subsequently surrounded by the herder was approximately 2,100 m^2, consisting of 1,500 m^2 of thick oil and 600 m^2 of thinner oil (Rainbow sheen and Metallic appearance oil). Approximately 40% of the available thick oil area, containing around 1.6 m^3 of oil, was herded, while 60% of the thick oil area containing around 2.2 m^3 of oil was not herded.

As illustrated in Figure 9.7, the herded thinner oil (Rainbow sheen and Metallic appearance oil) was very rapidly contracted "inwards" towards the thick (CTC) oil (yellow arrows), but also the thinner oil was also herded "outwards" (red arrows). The increase in the width of the clear water channel was due to both of these effects.

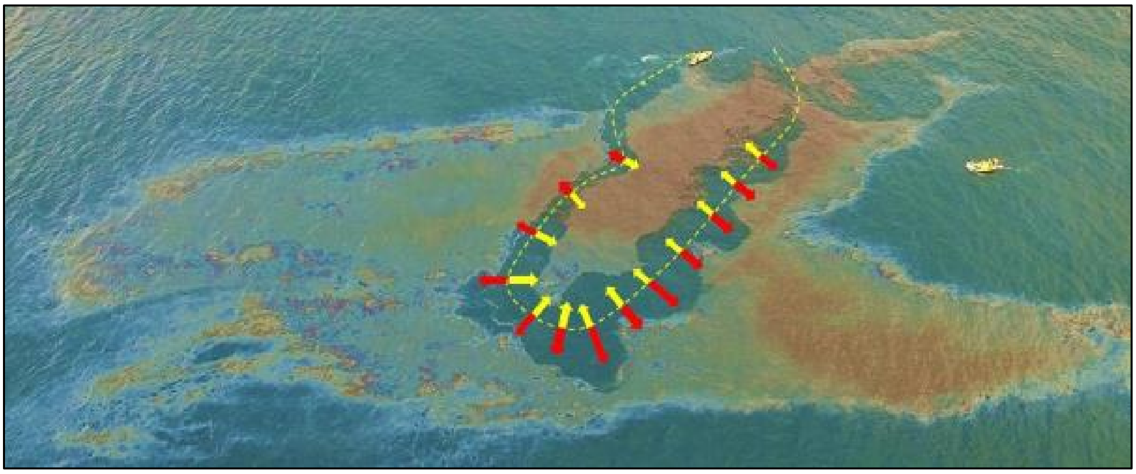


Figure 9.7 Effect of herder on oil layers of different thickness with HISB 4.3

The portion of thick oil that had been herded decreased in area over the next few minutes by a factor of 2 to 3 and the oil layer thickened. It is estimated that the average oil layer thickness increased from approximately 1.1 mm up to 2.1 to 3.2 mm.

9.3 Ignition and burning of oil

a. HISB 4.1

Three ignitions were attempted in the herded HISB 4.1 slick and all were successful. The initial burn began 51 minutes after the end of oil discharge. With some overlap, the three burns lasted 14 minutes (initial burn), 5 minutes (second burn) and 5 minutes (third burn) and the overall duration was 20 minutes.

It is known that approximately 20% of the oil was not herded and some of the oil that had been herded was not burned because there were separated patches of thick oil visible on the sea while burning was in progress (Figure 8.6).

About 75% of the herded oil, but with a range of 55% to 95%, was estimated to have been burned.

b. HISB 4.2

Three burns were ignited in the non-herded HISB 4.2 slick with eight ignitions attempted. The initial burn was ignited 51 minutes after oil release ended and lasted for three minutes. The second burn began one minute after the first and lasted for five minutes. There was a delay as more igniters were prepared and the third burn was ignited 75 minutes after the oil release ended. The overall burn duration was 13 minutes.

The total area of the HISB 4.2 slick before burning was 2,150 m^2 (+/- 10%). Approximately 300 m^2 was subject to burning during the first two burns and a maximum of approximately 200 m^2 to 300 m^2 during the third burn. This was because the slick had been sub-divided into several sub-sections by the passage of the MOB boats through the thick oil leaving tracks of much thinner oil that could not be burned.

On the basis that only half of the oil slick was ignited, it is estimated that approximately 25% (with a range of 20% to 30%) of the available thick oil was burned.

c. <u>HISB 4.3</u>

A single burn that separated into two discrete burn areas was ignited in the HISB 4.3 slick with the second of five attempted ignitions. The overall burn duration was 8 minutes.

The herded oil had become fragmented into several discrete areas and only two of these were burned. It is therefore estimated that 50% (with a range of 40% to 65%) of the area herded oil was burned.

Summary of oil ignition and burning

Figure 9.8 summarizes oil volumes from each experiment: oil released, estimated volumes after evaporation at sea, estimated oil volumes subjected to herding and estimated volumes subjected to burn.

Parts of the non-herded HISB 4.2 slick was successfully ignited because the average thickness of the thick oil area was 2.4 mm - 2.9 mm. Before herding, the average oil thickness in the HISB 4.1 and HISB 4.3 slicks were 1.1 mm - 1.6 mm and 1.0 mm - 1.3 mm, respectively. After herding, the average oil thickness in the herded areas of slicks HISB 4.1 and HISB 4.3 had been increased to 3.0 mm - 4.6 mm and 2.1 mm - 3.2 mm, respectively.

All three slicks had average oil layers with thickness in excess of 1 mm and ignition was therefore eventually successful in each case.

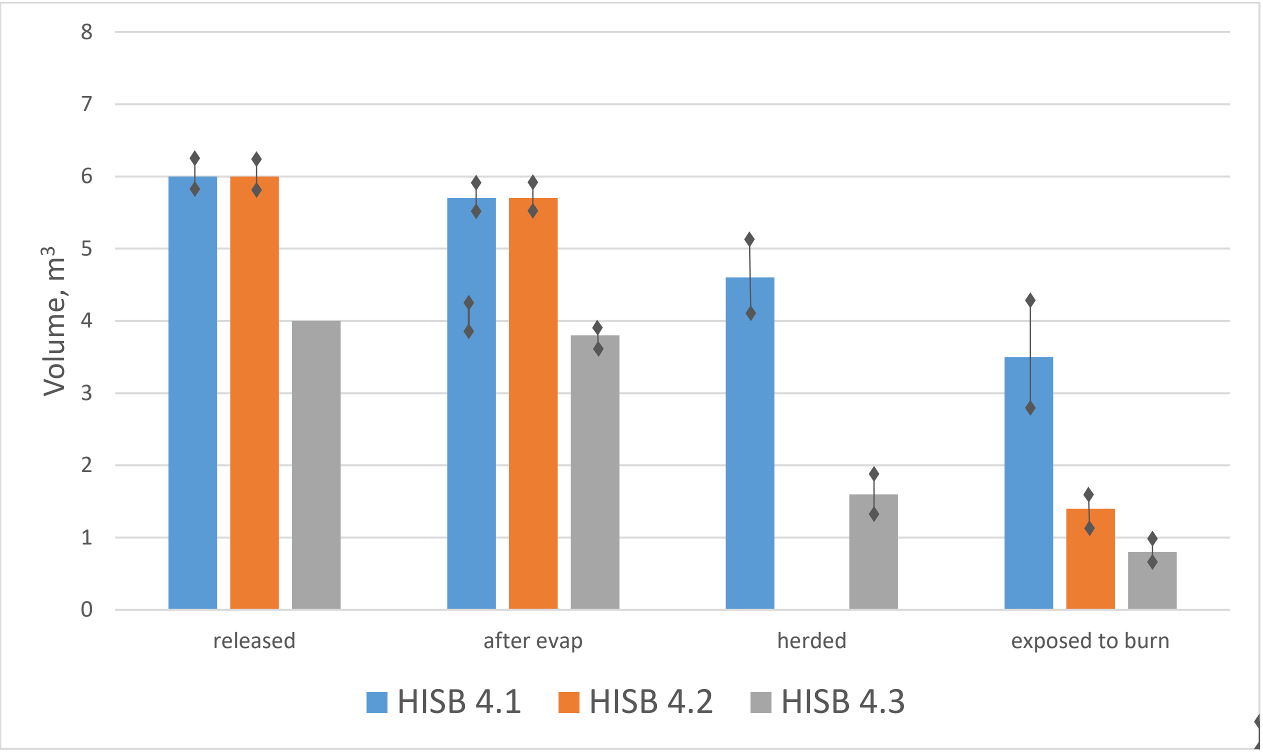


Figure 9.8 Oil volume released and estimated volumes after evaporation at sea, subjected to herding and subjected to burn. HISB 4.2 was not herded.

Table 9.1 contains a summary of the relevant parameters for each of the three experiments. By comparing the approximate volumes of oil subjected to burning in Figure 9,8 and Table 9,1 with the estimated volumes of oil burned in Table 9.2 it is possible to estimate a burn efficiency.

The amount of oil subjected to burning (ignited) in the three slicks was significantly less than the initial amount of oil released onto the sea:

- It is estimated that approximately 80% of the 6 m^3 of oil in the HISB 4.1 slick that was placed on the sea was herded. Approximately 75% (with a range of 55% to 95%) of this amount of thick oil was subjected to burning, indicating that only 3.5 m^3 (with a range of 2.5 to 4.4 m^3) of the oil could have been burned.
- It is estimated that only 25% (with a range of 20% to 30%) of the 6m^3 of oil placed on the sea in the HISB 4.2 slick was subjected to burning because the slick had been broken up into pieces by the transit of the MOB boats. This indicates that only 1.4 m^3 (with a range of 1.1 to 1.7 m^3) could have been burned.
- It is estimated that approximately 43% of the 4m^3 of oil placed on the sea in the HISB 4.3 slick was herded. Approximately 50% (with a range of 40 to 65%) of this amount of thick oil was subjected to burning, indicating that only 0.8 m^3 (with a range of 0.6 to 1.0 m^3) of the oil could have been burned.

The uncertainties in these estimates is high, as indicated by the wide ranges of areas and amounts of oil.

Table 9.1 Relevant parameters for HISB experiments

Parameter	Experiment		
	HISB 4.1	HISB 4.2	HISB 4.3
Volume of oil released (m^3)	6.0	6.0	4.0
Volume remaining after 5% evaporative loss (m^3)	5.7	5.7	3.8
Area of thick oil before herding (m^2)	4 250 (3 500 – 5 000)	2 150 (2 000 – 2 350)	3 500 (3 000 – 4 000)
Average oil layer thickness before herding (mm)	1.3 (1.1 - 1.6)	2.7 (2.4 - 2.9)	1.1 (1.0 - 1.3)
Area of available thick oil herded (% of total thick oil area)	80	N/A	43
Area of thick oil herded (m^2)	3 400 (2 800 - 4,000)	N/A	1 500 (1 300 – 1 700)
Area of thick oil after herding (m^2)	1 250 (1 000 – 1 500)	2 150 (2 000 – 2 350)	625 (500 - 750)
Volume of oil in herded area (m^3)	4.6	5.7	1.6
Average oil layer thickness after herding (mm)	3.7 (3.0 - 4.6)	2.7 (2.4 - 2.9)	2.6 (2.1 - 3.2)
Estimated area of thick oil subjected to burning (m^2)	950 (690 - 1,200)	500 (400 - 600)	300 (250 - 400)
Approximate percentage of available thick oil burned (%)	75 (55 to 95)	25 (20 to 30)	50 (40 to 65)
Approximate volume of oil subjected to burning (m^3)	3.5 (2.5 - 4.4)	1.4 (1.1 - 1.7)	0.8 (0.6 - 1.0)

Recovery of burn residue and treatment of unburned oil

The experience by using sorbent boom for containment and recovery of burn residue proved very difficult as the residue was very viscous and floated extremely heavy in the water. No conventional boom would probably been able to confine such heavy residue on the seawater, even in low sea state, as the residue will submerge easily under the boom shirt during a confinement operation. Even if we were able to confine some of the burn residue, only very small amounts were actually recovered. Samples were collected for analysis (see Appendix E).

Non-ignited parts of the slicks were treated with dispersants and totally 2.2 m^3 of Dasic NS was used.

Calculation of burn efficiency

With any ISB operation or experiment, it is often usual to report on 'burn efficiency'; the amount of oil that was burned as a percentage of the oil that was released. A gravimetric method, being used in several previous smaller ISB experiments, includes collection and weighting of the burn residue to withdraw that from the amount of oil released, to calculate the burn efficiency in percentage. This method have proven to be feasible for smaller contained burns (e.g. in ice-covered waters) and may even be possible for burns in fire-resistant booms. For larger burns on open water, this is much more complicated due to the large areas covered with burn residue and the challenge of recovering and weighting the entire residue. In these experiments, it proved to be impossible to use this method due to the problems with confining and recover the burn residue.

Another approach for calculating the burn efficiency is called the Integrated Time-Area (ITA). It requires accurate information on:

- Volume of oil spilled;
- Area of the slick that was burning;
- Duration of the burn; and
- Slick regression rate.

As described above, the amount of oil that was subjected to burning in each slick was significantly less than the amount of oil that had been placed on the sea and there are uncertainties in the estimates of oil areas and volumes.

The Integrated Time-Area (ITA) Approach (see Appendix G) was used to produce estimates of burn efficiency. In this approach, the flame area integrated over the duration of the burn is multiplied by an assumed burn rate. In this instance, the burn rate of fresh Grane crude as assumed to be a conservative 3.0 mm/min, based upon an estimated minimum starting 3 to 4 mm slick thickness.

The highest degree of uncertainty is in the estimates of the area of thick oil subjected to burning. The videos from the quadcopter drones were analysed to estimate the flame area of the burning oil and the duration for which the flames were present. Due to the presence of smoke and the three-dimensional nature of the flames, more than one image from different perspectives was required to estimate flame area and these areas could only be estimated with +/- 25% error. This error margin was due to limited availability of appropriate images and the inclusion of limited scaling items for photographic correction.

The estimates volumes of oil burned from this approach are presented in Table 9.2.

Table 9.2 Estimates of volume of oil burned from Integrated Time-Area (ITA) Approach

Experiment	Estimated volume of oil burned (+25% error) (m^3)
HISB 4.1	3.4 (2.5 - 4.3)
HISB 4.2	1.2 (0.9 - 1.5)
HISB 4.3	0.8 (0.6 - 1.0)

Comparison of the estimated volumes of oil subjected to burning (ignited) in Table 9.1 with estimated volume of oil burned in Table 9.2, based on the ITA approach, shows no significant differences in burn efficiency between the different experiments. The majority of the oil subjected to burning was burned, but the high degree of uncertainty precludes any meaningful analysis of the percentage of oil burned in each experiment.

9.4 Smoke plume analysis

Briefly, the mean levels of PM2.5-particles during burning were close to background concentrations, and below the Norwegian Air Quality Criteria (0.015 mg/m^3 for 24 hours).

Measurements taken from the drone showed high PM2.5 levels in the smoke plume (>8.5 to 10.8 mg/m^3), i.e., more than 1000 times higher than the background concentrations. PM2.5 levels dropped rapidly when the drone went out of the smoke plume. The total particle concentration (filter method) measured from the drone was very high (23.5 to 34.4 mg/m^3), which corresponds to estimated levels of 57 to 137 mg/m^3 when the drone was actually in the smoke plume (Norwegian OEL=10 mg/m^3). The sum of the 21 particulate PAH components in the two analysed samples were 2.3 and 12 $\mu g/m^3$, which correspond to estimated levels of about 9 and 29 $\mu g/m^3$ in the smoke plume (Norwegian OEL=40 $\mu g/m^3$). The PAH components in the vapour phase were in low concentrations in the two samples (naphthalene: 18 and 37 $\mu g/m^3$ and biphenyl: 0.56 and 1.4 $\mu g/m^3$). (The Norwegian OELs are 50 mg/m^3 for naphthalene and 1 mg/m^3 for biphenyl).

Measurements on the Coast Guard vessel showed levels of particles/dust on the filters below the limit of detection (<0.1 mg), and was thus not analysed for PAH components.

In conclusion, the concentration of PM2.5 particles was low in both the USV and the Coast Guard vessel and also during the actual burning process. At the Coast Guard vessel the concentration of total particles was below the limit of detection when the filter method was used.

As expected the concentrations of PM2.5 particles and total particles were high in the smoke plume, by far exceeding the air quality criteria and limit values, but declined rapidly when the drone left the smoke plume. In the smoke plume particulate PAH components were detected at levels approaching the Norwegian OELs. PAH in the vapour phase was low. The short sampling times due to the short burning process, and the low air flow rate through the filters led to a low amount of sampled particles/dust/PAH on the filters, and have increased the uncertainty of filter measurements (total particles and PAH-component profiles). Nevertheless, the results indicate that human exposure to hazardous compounds from the actual burning process was very low or negligible on the vessels upwind from burning of these oil slicks. Further details from the smoke plume analyses can be found in Appendix F.

10 CONCLUSIONS AND RECOMMENDATION

10.1 Conclusions

The following conclusions were drawn:

1. The experiments demonstrated that oil slicks in open waters with wind speeds up to 5 m/s can be effectively contracted by herder sprayed from a small boat around the periphery of thick areas of oil in a slick.
2. The two slicks treated with herder showed increased thickness for the herded areas followed by successful ignition. Parts of the non-herded reference slick were also successfully ignited because the average thickness of the thick oil remained well above the minimum thickness for ignition within the one hour waiting period after release.
3. Under the very light wind and very calm sea conditions, the spreading of the more compact reference (HISB 4.2) slick was more limited than that of the other two slicks. The average oil layer thickness in the thick oil areas of the slick was 2.7 mm when igniters were used. The oil ignited, even though the oil had not been herded. This was most probably tied to the constraint of having to follow the permitted trial procedures that did not allow the experimental slicks to remain on the sea surface for a longer time, combined with the release conditions with a concentrated release of the oil in the calm sea conditions. In a real oil spill the oil would have been given more time on the sea surface before applying herder and the oil would have spread out into a thinner oil layer potentially below what is regarded as the minimum thickness for ignition of an oil slick.
4. The greatest difficulty was in observing and locating the areas of thick oil in the slicks from the small boats. The lack of real-time positional awareness of where the boats were located relative to the slicks themselves, led to some inaccuracies in applying herder followed by fragmenting of two of the experimental slicks into separated thick oil areas when the boats inadvertently traversed through them before and during ignition. For all three slicks, a direct downlink of video from aerial oversight platforms to the herder application vessels would have greatly improved operations and the portions of the slicks subjected to herder treatment and burning.
5. It was estimated that the most oil was burned in the HISB 4.1 slick while less was burned in the herded portion of the HISB 4.3 and in the non-herded HISB 4.2 slick. The herded HISB 4.1 slick was not fragmented as the herded portion of the HISB 4.3 slick and the non-herded HISB 4.2 slicks were.
6. The higher wind speeds encountered in the HISB 4.3 experiment were one factor in reducing the volume of oil burned because the oil spread into areas of thin and thick oil. Only a minority of the thick oil area was herded. Again, direct aerial oversight and guiding would have improved the targeting of the herder application, the disposition of the igniters and improved the overall burn efficiency of this slick.
7. Use of sorbent boom and nets for burn residue recovery proved challenging given difficulties with confining the very viscous and heavy residue. The tendency of the residue to float partly submerged led to problems tracking the burn remnants of the slick over time.
8. The analysis of particles and PAH components in the smoke plume itself indicated high levels of particles and a PAH "footprint" comparable to previous oil burns (e.g. Deepwater

Horizon). For vessels placed upwind of the smoke plume, human exposure to hazardous compounds was found to be very low or negligible.

10.2 Recommendations

A Memo summing up lessons learned from the field trial was prepared with the aim of improving future field trials. The following main recommendations are based on experience from the ISB experiments:

- The short endurance quadcopter drones used to monitor the experimental slicks had video, but no thermal IR (Infrared). This limited the ability to discriminate between thick and thin oil areas. Most importantly, there was no image down-link to the MOB boats to provide real-time effective positional awareness. Malfunction of the Aerostat (Ocean Eye) was a further drawback for monitoring of surface oil and for providing sustained guidance during herder and ignition operations. Use of remote sensing aircraft could not fully compensate for this lack of coverage and their operations were hindered without prior warning by a 2-hour failure of ATC (Air Traffic Control) in southwestern Norway. When small boats are used for HISB operations, better aerial surveillance, and communication between observers and application crew, are essential:
    - for locating the perimeter of the slick to allow effective herder application; and
    - for locating thick upwind portions of the slick to allow effective igniter application
- Drone and remote sensing aircraft operations were performed much as planned apart from the obviously unforeseen failure of ATC (Air Traffic Control). Some gaps in documentation could have been avoided through better communication with release crews from those responsible on the bridge and better communication and information from the spill site to flight crews. The essential missing element was direct video downlink from the aerial platforms to the crews on the herder/igniter application boats – the availability of real-time imagery to small boat crews in future will greatly improve the entire herder/burn operation.
- Further field trials involving large-scale application of herder followed by ignition, for instance as part of future Oil On Water field trials in Norway, will provide better field estimates of likely burn efficiencies achievable with this countermeasure and improved insights on weather limitations. Additionally, use of in-situ burning as an oil spill response in future actual spills ("spill of opportunity") would also contribute to improved understanding of the potential with this method.
- Testing of full size herder application systems based on a helicopter or other aerial delivery platform would help minimize and/or eliminate issues related to the challenge of reliably seeing oil from the water surface under different lighting and sea conditions. Helicopter-deployable systems inherently benefit from having a "birds eye-view" of a slick, and would also be useful as an additional platform for photographic and video monitoring of the slick.
- The Grane Blend crude oil used in these experiments is an asphaltenic crude oil leaving a very sticky non-solidified burn residue. In contrast to residues from paraffinic oils, that may have a tendency to solidify, the sticky Grand Blend residue is more difficult to confine and recover. Residues from free floating slicks treated with herder tend to be more difficult to recover because the spreading of oil is larger and the burn residue is more

difficult to monitor. Therefore, there is a need for further testing and development of more advanced methods for recovery of free-floating burn residues.

In the future it is expected that remotely operated small vessels and drones fitted with thermal IR cameras could play a larger role in field experiments providing monitoring and remote sensing information important for successful operations.

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- Norwegian Coast Guard

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- Finnish Border Guard/SYKE; Aircraft: OH-MVO
- Netherlands Coast Guard; Aircraft: PH-CGN
- Norwegian Coastal Administration; Aircraft: LN-KYV

Drone remote sensing, smoke sampling and video footage provided by:

- Maritime Robotics

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APPENDIX A DESCRIPTION OF THICKSLICK 6535

ThickSlick 6535 is one of two herding agents listed on the U.S. EPA National Contingency Plan (NCP) Product Schedule for consideration for use on spills in U.S. waters. ThickSlick 6535 is a blend of 65 volume % sodium monolaurate (Span 20), the surfactant, and 35% 2-ethyl butanol solvent. The active ingredient of ThickSlick 6535 is used as a food additive, in household cleaners as well as in cosmetics, fine fragrances and other toiletries. A Material Safety Data Sheet is available for ThickSlick 6535 from DESMI.

Table A.1 Summary Results for U.S. EPA Approval for Listing on NCP Products Schedule

TEST		ThickSlick 6535	Siltech OP-40
	Units	Results	Results
NCP Category		Surface Collecting Agent	Surface Collecting Agent
Analytical tests			
Key Findings Summary			
Flash Point		>180 °F (82°C)	>180 °F (82°C)
Pour Point		21.2 °F (-1.7°C)	-74.2 °F (-59°C)
Viscosity	cSt	24.7	8.27
Viscosity @100°F	SUS*	118	53
Specific Gravity@60°F (15°C)		0.974	0.988
Surface Collecting Agent Test		PASS	PASS
Phase Separation		None	None
Freezes at		11.2°F (-24°C)	-95.8°F(-71°C) ((-71°C)
Solubility		Partial Miscibility	Partial Miscibility
pH		6.45	10.1
Toxicity tests			
Herder			
M. bahia 48-hr	ppm	286	6.83
M. beryllina 96-hr	ppm	138	3.33
No.2 Fuel Oil			
M. bahia 48-hr	ppm	2.43	6.43
M. beryllina 96-hr	ppm	37.6	40.5
10:1 No.2 Fuel Oil / Herder			
M. bahia 48-hr	ppm	1.53	3.27
M. beryllina 96-hr	ppm	5.91	9.7
Reference Toxicant-			
M. bahia 48-hr	ppm	8.23	8.68
M. beryllina 96-hr	ppm	3.02	2.33

* Saybolt Universal Seconds

APPENDIX B DRONE- OPERATIONS PERFORMED BY MARITIME ROBOTICS DURING THE NOFO OPV FIELD TRIAL 2016

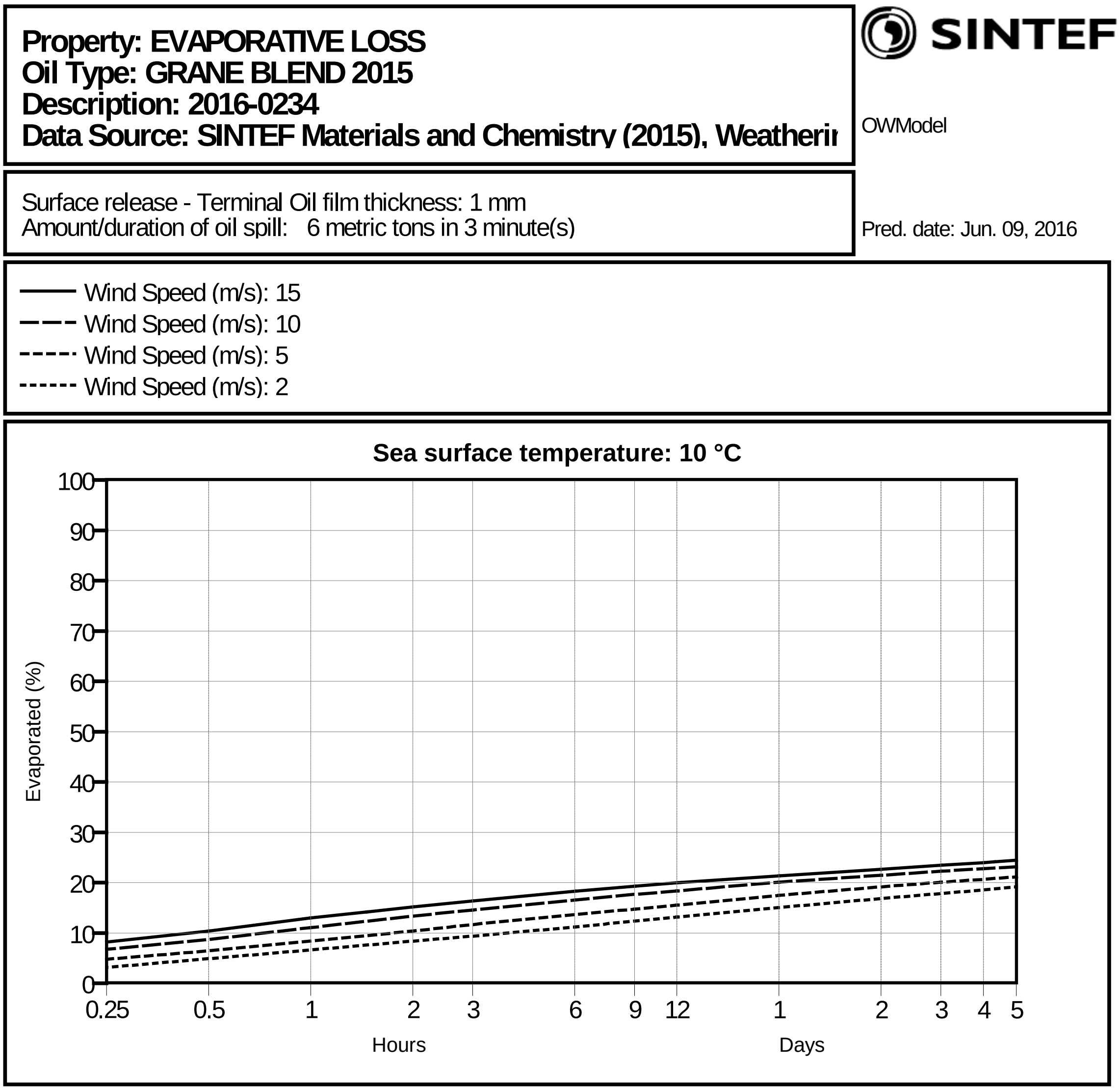
During the field trial, Maritime Robotics provided drone flight support to document aspects of the trials. Drones in operation were 2 camera drones and 1 drone flying with smoke sampler equipment. The following gives an overview of the drones in operation during the different experiments, and an estimate on how much documentation is made available for each trial.

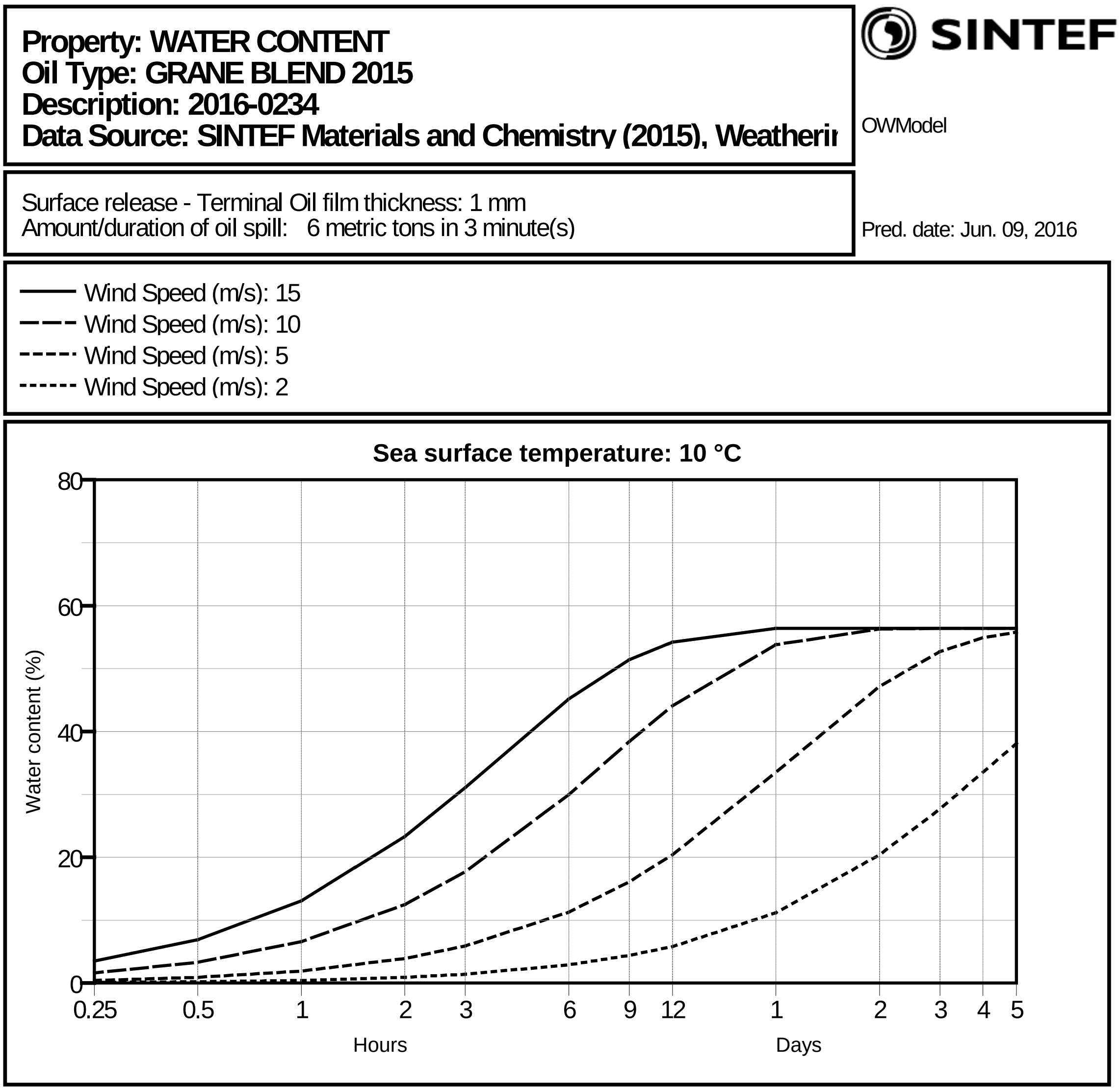
The smoke sampler drone flew during the burns on day 1. Because of the nature of the flight profile, it is impossible to know exactly how much sampling time was done for each burn. The video drones collected video of the oil slicks, herding and burning. In the table below, the recording time is documented.

Drone flights and experiments:

Experiment	Drone	Description	Time	Video
3.1	Video drones Smoke sampler drone	Drone flights for pilot calibration and video angle testing. No video.	-	-
3.2	None		-	-
HERDER/ BURNING 4.1	Video drones Smoke sampler drone	4 video drone sorties. Results of herder application on video. Video of burning. Smoke sampling 10-15 min.	14:00 – 14:30	20 min
HERDER/ BURNING 4.2	Video drones Smoke sampler drone	Large continuous film clips, 2 gaps between flights. 3 video drone sorties. Shows mob boat splitting the slick, then burning. Smoke sampling 10-15 min.	15:51 – 17:08	32 min
HERDER/ BURNING 4.3	Video drones Smoke sampler drone	Large continuous film clips, 2 gaps between flights. 3 video drone sorties. Video of release, herding and burn. Smoke sampling 10-15 min.	19:04 – 20:07	35 min
TOF 3.3 FIFI	1 Video drone	Problematic to fly drone off the ship, which is spraying with water. Wind close to margins made drone flights hard when ship was going against the wind. 1 video drone sortie.	12:52 – 13:05	13 min
HERDER in water	Video drone	Approximately 40min flying during this test. 2 video drone sorties.	16:44 – 17:16	31 min

APPENDIX C SINTEF OWM PREDICTIONS FOR 6 M³ RELEASE OF GRANE BLEND CRUDE




Property: WATER CONTENT
Oil Type: GRANE BLEND 2015
Description: 2016-0234
Data Source: SINTEF Materials and Chemistry (2015), Weatherir
SINTEF
OWModel
Surface release - Terminal Oil film thickness: 1 mm
Amount/duration of oil spill: 6 metric tons in 3 minute(s)
Pred. date: Jun. 09, 2016
Wind Speed (m/s): 15
Wind Speed (m/s): 10
Wind Speed (m/s): 5
Wind Speed (m/s): 2
Sea surface temperature: 10 °C
Water content (%)
0
20
40
60
80
0.25
0.5
1
2
3
6
9
12
1
2
3
4
5
Hours
Days

Property: VISCOSITY OF EMULSION
Oil Type: GRANE BLEND 2015
Description: 2016-0234
Data Source: SINTEF Materials and Chemistry (2015), Weatherir

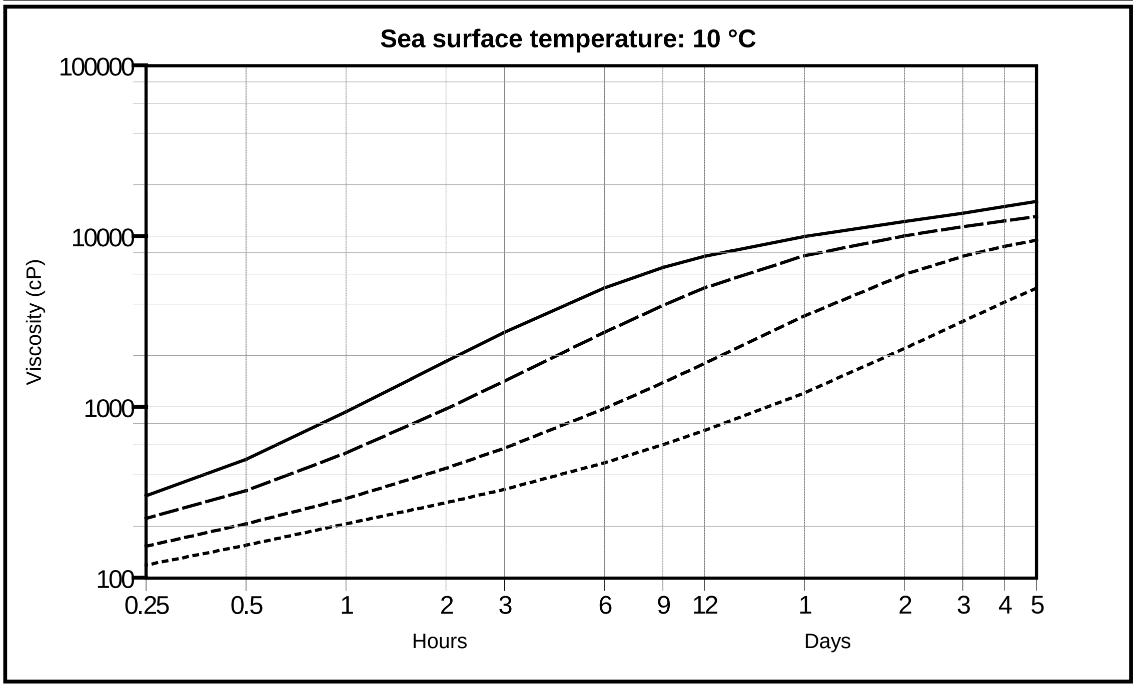
SINTEF

OWModel

Surface release - Terminal Oil film thickness: 1 mm
Amount/duration of oil spill: 6 metric tons in 3 minute(s)

Pred. date: Jun. 09, 2016

- Wind Speed (m/s): 15
- Wind Speed (m/s): 10
- Wind Speed (m/s): 5
- Wind Speed (m/s): 2



Property: POUR POINT FOR WATER-FREE OIL
Oil Type: GRANE BLEND 2015
Description: 2016-0234
Data Source: SINTEF Materials and Chemistry (2015), Weatheri

SINTEF

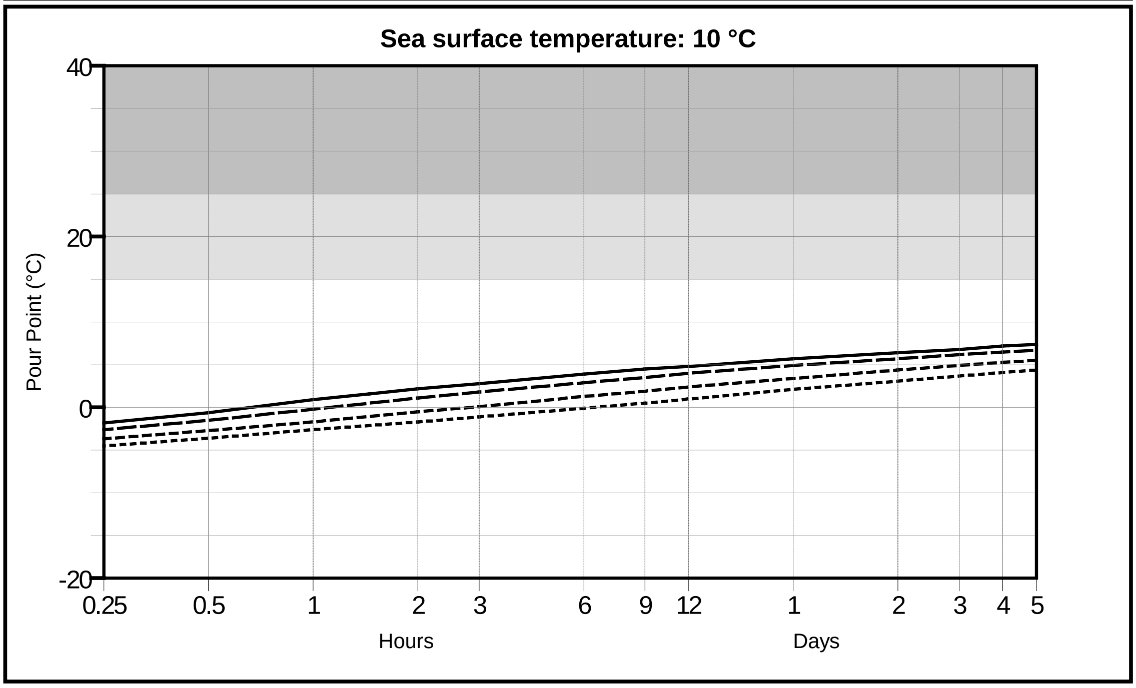
OWModel

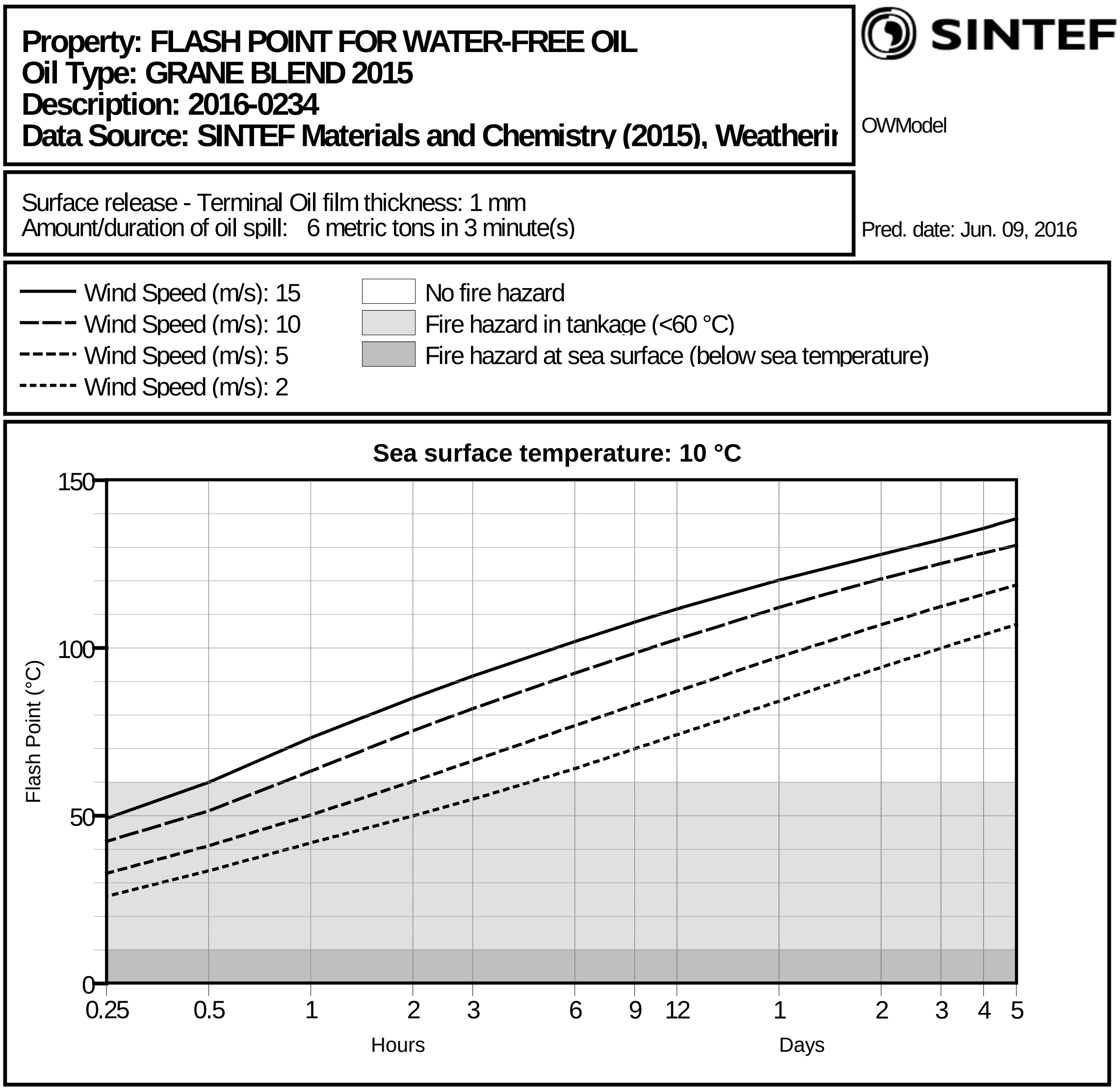
Surface release - Terminal Oil film thickness: 1 mm
Amount/duration of oil spill: 6 metric tons in 3 minute(s)

Pred. date: Jun. 09, 2016

Wind Speed (m/s): 15
Wind Speed (m/s): 10
Wind Speed (m/s): 5
Wind Speed (m/s): 2

Chemically dispersible
Reduced chemical dispersibility
Poorly / slowly chemically dispersible




Property: FLASH POINT FOR WATER-FREE OIL
Oil Type: GRANE BLEND 2015
Description: 2016-0234
Data Source: SINTEF Materials and Chemistry (2015), Weatherir
SINTEF
OWModel
Surface release - Terminal Oil film thickness: 1 mm
Amount/duration of oil spill: 6 metric tons in 3 minute(s)
Pred. date: Jun. 09, 2016
Wind Speed (m/s): 15
Wind Speed (m/s): 10
Wind Speed (m/s): 5
Wind Speed (m/s): 2
No fire hazard
Fire hazard in tankage (<60 °C)
Fire hazard at sea surface (below sea temperature)
Sea surface temperature: 10 °C
Flash Point (°C)
150
100
50
0
0.25
0.5
1
2
3
6
9
12
1
2
3
4
5
Hours
Days

Property: MASS BALANCE
Oil Type: GRANE BLEND 2015
Description: 2016-0234
Data Source: SINTEF Materials and Chemistry (2015), Weatherir

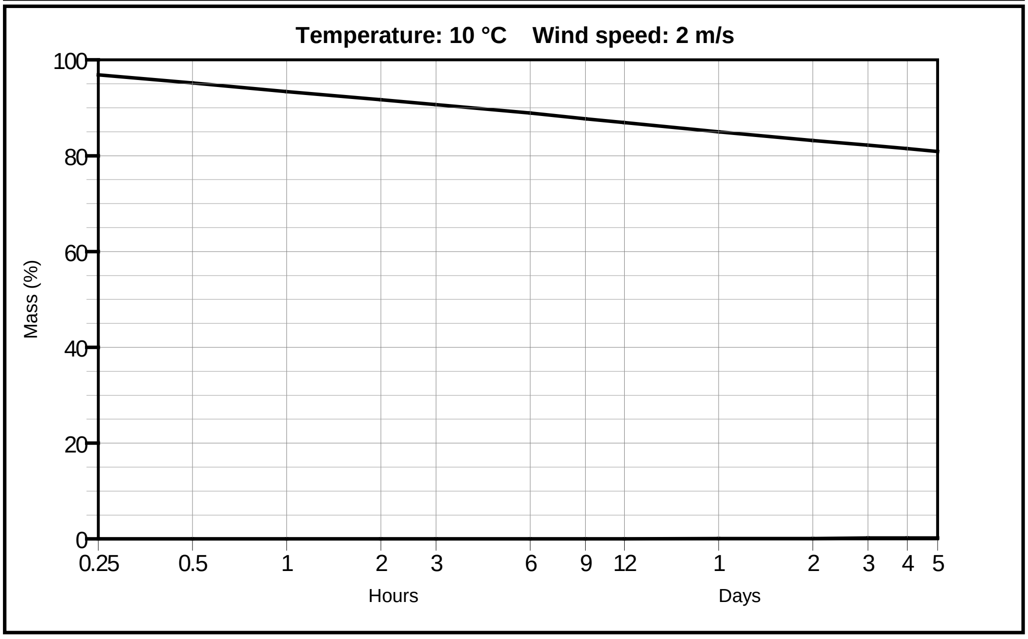
SINTEF

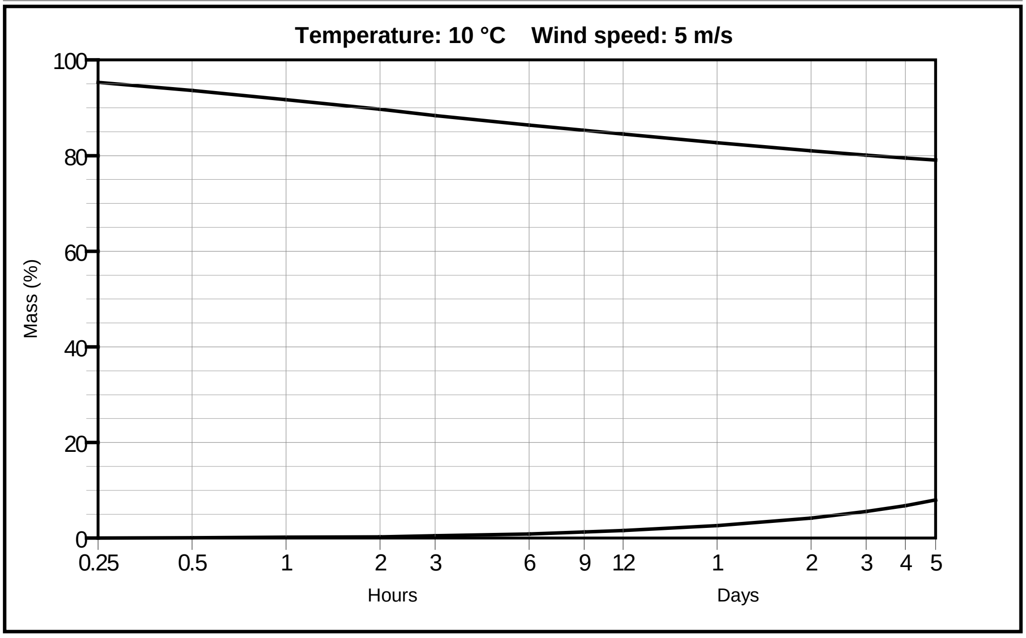
OWModel

Surface release - Terminal Oil film thickness: 1 mm
Amount/duration of oil spill: 6 metric tons in 3 minute(s)

Pred. date: Jun. 09, 2016

Evaporated
Surface
Naturally dispersed





APPENDIX D AIRCRAFT SURVEILLANCE DURING THE NOFO 'OIL ON WATER' FIELD TRIAL 2016

A total of 10 missions, five on each day, were flown by the three available aircraft.

The aircraft were not tasked solely on the experimental slicks. They also gathered information for NOFO on the other activities on the exercise.

The Norwegian aircraft is chartered by Kystverket (Norwegian Coastal Administration) and NOFO and the data is theirs.

The Finnish and the Netherlands aircraft were there on a no-cost to NOFO basis; it is part of the Bonn Agreement and HELCOM arrangements to invite then so that they could 'see' real oil on the water in controlled conditions. The cost for the aircraft and crews attending was borne by the Netherlands and Finnish Governments and the data gathered is theirs. They must be given proper credit in any reports etc. All images from the Finnish aircraft are all marked "© Finnish Border Guard / SYKE". The data from the Netherlands aircraft will be the same.

Total data haul

	Aircraft	Local time Images		File size (Gb)	# folders	# files
Tuesday 14th		First	Last			
OOW14.01	Norway	08:12	09:34	3.90	25	115
OOW14.02	Finland	10:12	11:58	3.93	9	352
OOW14.03	Netherlands	13:44	14:31	2.99	14	216
OOW14.04	Norway	16:01	17:37	10.0	60	254
OOW14.05	Finland	17:51	19:28	2.94	9	322
Wednesday 15th						
OOW15.01	Norway (1)	08:33		0.725	14	69
OOW15.02	Norway (2)		11:23	5.19	35	146
OOW15.03	Finland	12:38	13:43	3.23	9	253
OOW15.04	Netherlands	14:22	15:29	0.725	14	69
OOW15.05	Finland	17:04	18:48	3.10	9	155
				36.73	**198**	**1,951**

PRELIMINARY SUMMARY OF DATA GATHERED

Tuesday June 14th					
Event at sea	Aircraft	Start	Video / FLIR	Photos	UV/IR scans
Local (UTC)		Local Time			
08:45 - 08:50 (06:45 - 06:50) Slick 3.1 release Start 08:43:16 @ N60°0.0799' E2°23.429'	Norway	8:12	15 videos (each of HDTV, HDIR and HDZ) From 08:12 to 09:34 Local Time		
10:03 – 10:09 (8:03 – 8:09) Slick 3.2 release Not observed by aircraft					
Dispersant spray 1 10:28 – 10:31 Dispersant spray 2 10:39 – 10:42 Dispersant spray 3 10:44 – 10:45 Dispersant spray 4 10:48 – 10:51	Finland	10:08	20 videos (Visual and FLIR) From 10:12 to 11:58 Local time		
13:21 – 13:23 (11:21 – 11:23) Slick 4.1 release (Not Observed by Aircraft)	No aircraft on-site because of failure of air traffic control in western Norway from approximately 11:00 to 13:00 local time. No aircraft take-offs allowed during this period.				
13:53 – 14:00 Herding *(11:53 – 12:00)* 14:10 – 14:15 First Ignition *(12:10 – 12:15)* 14:14 – 14:28 3 separate burns in slick *(12:14 – 12:28)*	Netherlands	13:44	38 videos (Visual and FLIR) From 13:44 to 15:31 Local time	A total of 157 photographs	

Tuesday June 14th (continued)					
Event at sea	Aircraft	Start	Video / FLIR	Photos	UV/IR scans
Local (UTC)		Local Time			
15:00 - 15:30 (13:00 - 13:30) Sorbent booming of residue 15:40 - 15:43 (13:40 - 13:43)					
16:05 - 16:20 (14:05 - 14:20) MOB B, 1st. sampling of surface oil 16:33 – 16:35 (14:33 - 14:35) MOB– C splitting the slick, Flare put in down-wind area 16:34: – 16:40 (14:34 - 14:40) Main burn 17:00 (15:00) New flares. New ignition 17:00 – 17:06 (15:00 – 15:06) Second burn	Norway	16:01	17 videos (each of HDTV, HDIR and HDZ) From 16:01 to 17:37 Local time	A total of 12 photographs	
KV Sortland (16:13) Strilborg in 3rd oil slick 18:08 (16:08) (dispersing remnants of 4.2 slick) Slick 3.1 and 3.2 18:31 (16:31) Desmi boom failure 18:55 (16:55) Desmi boom failure 19:00 (17:00) Desmi boom failure 19:25 (17:25	Finland	17:51	20 videos (Visual and FLIR) From 17:51 to 19:28 Local time		27 UV/IR Line scans between 17:59 and 19:25 Local time

Wednesday June 15th					
Event at sea	Aircraft	Start	Video / FLIR	Photos	UV/IR scans
Local (UTC)		Local Time			
	Norway (1)	08:00			
	Norway (2)	10:00			
09:07 Current Buster 09:09 Current Buster 09:19 Current Buster (Stril Luna) 09:22 Strilborg / KV Sortland W342 09:27 Current Buster / Bøen LJSY 09:43 Current Buster 09:50 Current Buster			19 videos (each of HDTV, HDIR and HDZ) From 08:33 to 11:23 Local time		
Aircraft tasked to slicks in UK waters Fi-Fi from Strilborg 13:14 (11:14) Strilborg Fi-Fi 13:31 (11:31)	Finland	12:05	6 videos (Visual and FLIR) From 12:38 to 13:43 Local time	73 photos from 12:58 to 13:40 Local time	9 UV/IR Line scans between 12:45 and 13:20 Local time
	Netherlands	14:05	7 videos (Visual and FLIR) From 14:22 to 15:29 Local time	28 photos from 14:09 to 15:02 Local time	
16:49 Expt. 4.4 Release 4 L of Herder Remnants of FiFi slick 18:40:-18:50 More FiFi treatment. Guided to area by the Finnish aircraft.	Finland	16:05	10 videos (Visual and FLIR) From 16:45 to 18:48 Local time	8 photos 4 photos of herder 4 photos of oil 8 photos of FiFi	9 scans of herder 2 scans of oil

APPENDIX E PROPERTIES OF BURNED RESIDUES / GROUND TRUTH DATA FROM SAMPLING BOATS

In order not to disturb the spreading of the 4.1 slick, no MOB-boats went into the slick for surface sampling prior the herder / ignition operation. Therefore, no ground-truth data of film thickness measurement and oil properties were made prior burning. Two samples of burned residues were taken at two positions after the termination of the burning.

Figure. E.1 show the GC-chromatograms of the fresh Grane Blend, the 250°C+ laboratory topped residue, and the GC of one of the two sample burned residue of slick 4.1. Compared to fresh oil, the residue show wide "span" in components that have been exposed due to the burning. Traces of components can be seen from C_{10}, at the same time that components up to C_{30-35} are partly influenced by the burn.

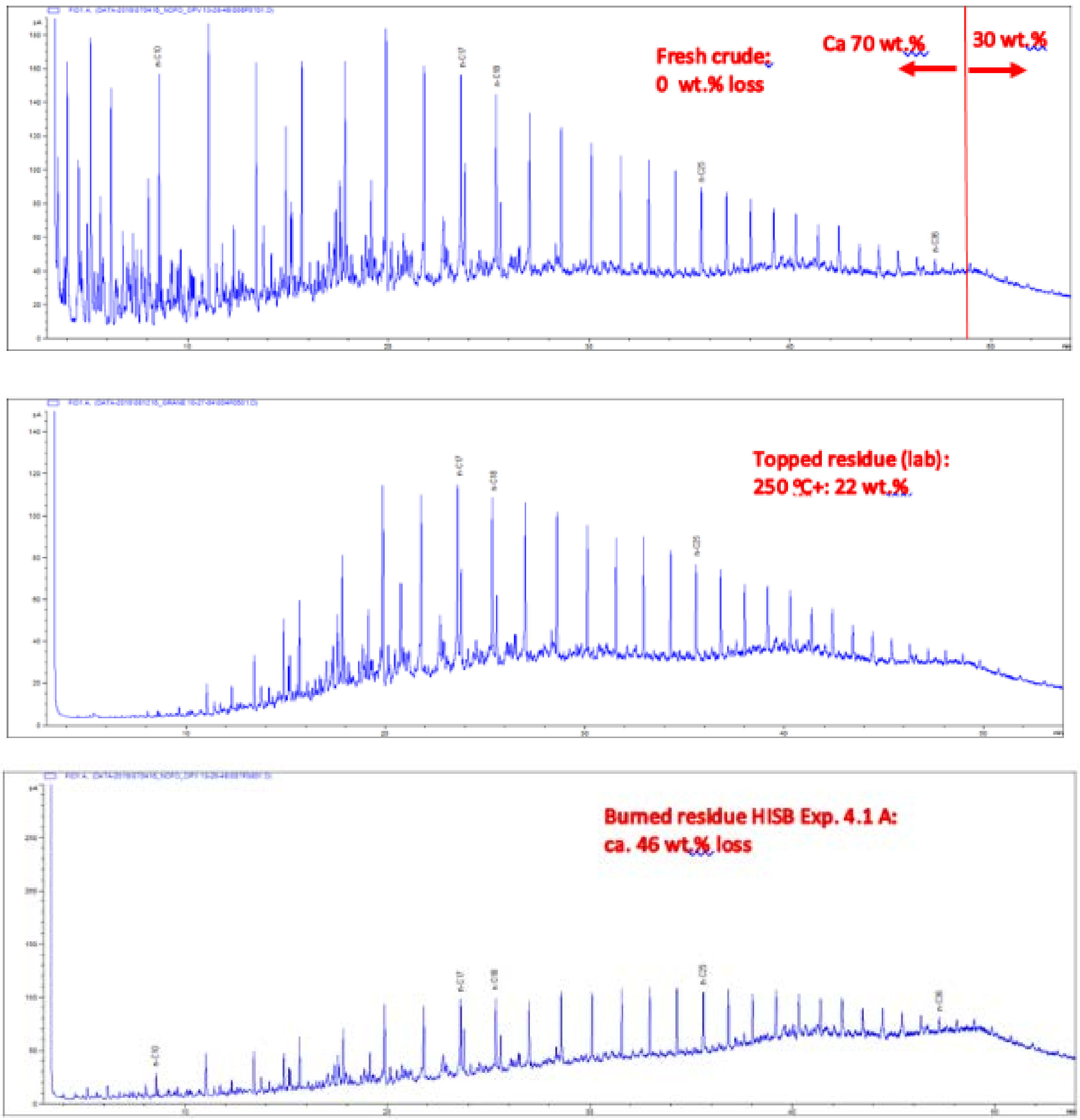


Figure E.1 GC-chromatograms of Grane Blend A: Fresh crude, B: laboratory topped residue at 250°C+, giving a quantified evaporative loss of 22 wt%., C: Burned residue (sample 4.1.A)

Prior physico-chemical characterization at SINTEF Laboratories, the burned residues were heated up to 50°C in order to have a homogenous, floating liquid without any possible gas (air) "pockets" inside the material. The density were quantified by volume/gravimetric measurements. Table E.1 showed the measured densities of the fresh crude, laboratory topped and burned residues of the Grane Blend. Based on these measurements, a linear regression between density and wt. % of topping degree was generated (see Figure E.2). Based on this correlation, an estimation of wt. % loss in the burned residues have been made.

Table E.1 Density and evaporative loss of Grane Blend (laboratory and field data, 4.1 and 4.2)

Oil	Density (Kg / L)	Evaporated (wt%)	Evaporated (vol %)
Fresh	0,900	0	0
Topped (150°C+), SINTEF Lab.	0,919	7,9	9,8
Topped (200°C+), SINTEF Lab.	0,931	14,8	17,7
Topped (250°C+), SINTEF Lab.	0,941	22,1	25,5
Atm. Distil. (370°C+, crude assay data)	0,972	43,1	-
Vac. Dist (550°C+, crude assay data)	1,019	76,3	-
Surface sample, 4.2 (15min. after release)	0.914	< 5*	
Burned residue, 4.1. A (Field sample)	0,978	46*	-
Burned residue, 4.1. B (Field sample)	0,967	39*	-
Burned residue, 4.2. (Field sample)	0,952	30*	-

*) Quantification of evaporative loss from the burned residues in release 4.1 (two samples) and 4.2. (one sample) bases on linear regression (see Figure D-2)

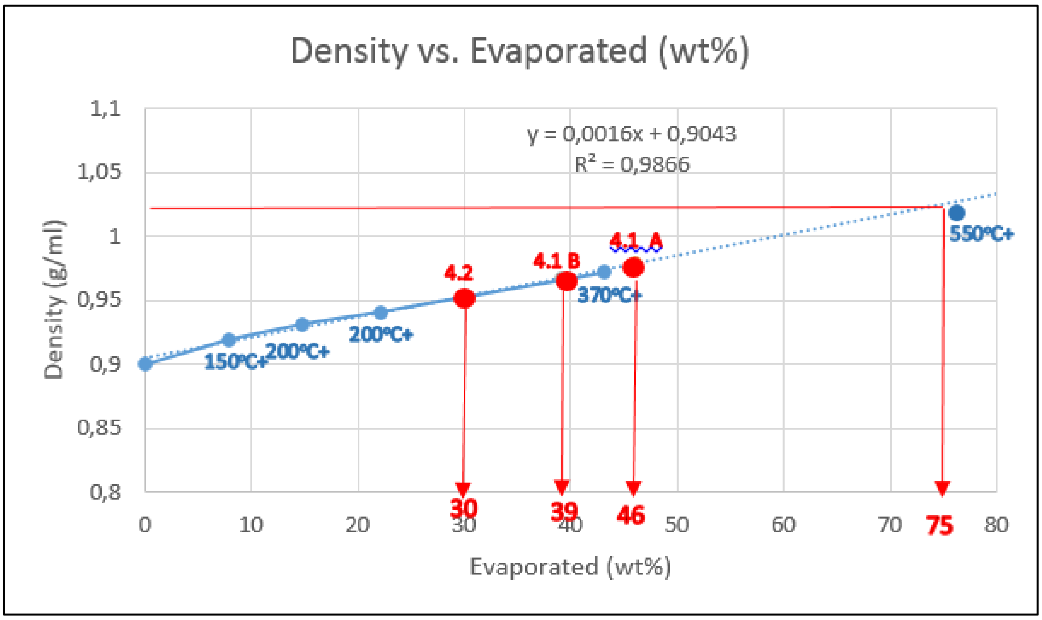


Figure E.2 Correlation (linear regression) between the densities and evaporative loss by topping of the Grane crude.

The material had an extreme high viscosity. The rheology-meter were not able to measure viscosities with shear rate 10 s^{-1} at lower temperature than 30°C (620.000 mPa s). A shear rate of 2 s^{-1} at 13°C, gave a viscosity of 20-25 million mPas.

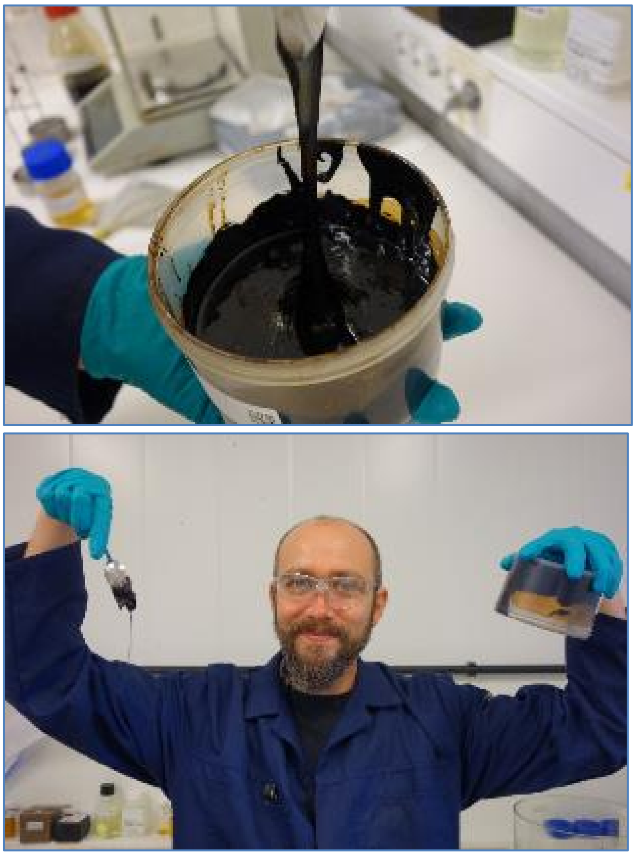


Figure E.3 Photos of samples of burned residues, for characterizations at SINTEF Laboratories

Although the analysis is of interest for other reasons, it is not possible to correlate residue density or characterization with burn removal efficiency, for the following reasons.

Combustion is a vapour-phase phenomenon. The key oil slick parameter that defines whether or not the oil will burn is slick thickness; if the oil is thick enough it acts as insulation and keeps the burning slick surface at a high temperature by reducing heat loss to the underlying water. As the slick thins, increasingly more heat passes through it; eventually enough heat is transferred through the slick to causes the surface oil temperature to drop below its fire point, at which time burning stops quite suddenly.

The process by which oil vaporizes is not a distillation (whereby the lightest, most volatile components are boiled off from the entire slick first followed by progressively heavier, less volatile components) but is similar to an imperfect Equilibrium Flash Vaporization (EFV) in which vapour of essentially constant composition is produced over time by boiling liquid oil of essentially constant composition. It is believed that EFV occurs during in situ burning because the hot flames and the insulating characteristics of the oil combine to create high heat inputs to the oil surface layer and high surface temperatures in a thin layer known as the "hot zone". This promotes near-complete vaporization of successive layers of the oil slick with minimal mixing and heat transfer to the underlying oil and/or water layers. It is termed imperfect EFV because some of the heaviest components of the crude oil cannot be vaporized and concentrate in the residue as burning proceeds.

In summary, the steady state phase of in situ burning is controlled by radiant heat transfer from the flames back to the surface of the burning slick; this heats and vaporizes a thin surface film of oil which subsequently burns in the air above the slick. The combustion stops when the slick is so thin (about 1 mm) that that it can no longer provide enough insulation to keep its surface sufficiently hot. The residue will always contain some light components from the unburned 1-mm remaining at extinction and an abundance of heavy components from the inefficiency of the EFV. The presence of these light ends and concentrated heavy components mean it is not possible to simply correlate GC analysis or density of the burn residue with oil mass removal efficiency of ISB.

APPENDIX F AIR SAMPLING OF PARTICLES AND HYDROCARBONS DURING IN-SITU BURNING OF OIL SPILL

Purpose:

This Oil In-Situ Burn (ISB) Smoke Sampling Plan is directed at obtaining data for completing Task 6 of the contract, "Conduct air sampling of hydrocarbons during in situ burning of oil spill and provide analysis report to JIP Technical Working Group".

Measurements in the smoke plume would provide us with the air concentrations of particles and with PAH "footprint" of the particulate PAH from the specific oil tested. The measured levels in the closest vessels would indicate the potential exposure level for humans closest to the smoke. Dispersion models were not a part of this task.

Background

The primary health concern in emissions from burning of oil spill is related to particles, Polycyclic Aromatic Hydrocarbons (PAHs) in the soot and the gaseous emission (Mullin & Champ, 2003, Fingas, 2014). The small, respirable particles have raised the most serious concerns, and although their concentrations decline rapidly downwind from the fire, relatively high concentrations have been measured at ground level. The soot particles consist of carbon, and a number of absorbed chemicals, including PAHs. Experimental burns have found that compared to the original oil, the soot contained a similar or higher concentration of some higher molecular weight PAHs which are the most toxic, and lower concentration of lower molecular weight PAHs (Evans et al., 2001). However, the overall concentration of PAHs in the soot and residue is less than in the original oil. Previous investigations have shown PAHs as gaseous emission from crude oil fires are negligible. Another concern in the gaseous products in the smoke is volatile organic compounds (VOCs) such as benzene, toluene, ethylbenzene and xylene (BTEX). However, in experimental burns these compounds have been detected in very low concentrations downwind of the burn (Mullin & Champ, 2003).

In the present project our aim was to perform air sampling at two locations;

1) in or close to the smoke plume

2) in the vessel planned to be closest to the smoke plume

We planned to focus on measurements of $PM_{2.5}$-particles, PAHs in soot/particles in the "total" dust fraction and BTEX in the vapour phase.

Methods

Project group UiB;

Magne Bråtveit, professor, Occupational Hygiene

Bjørg Eli Hollund, researcher/PhD, Occupational Hygiene

Jorunn Kirkeleit, researcher/PhD

Ingrid Gjesteland, chemist/PhD-student

From Sintef:

Daniel Krause, Senior Engineer

Source of Emissions:

Air measurements were taken during three Oil ISBs involving Grane crude oil: one involving herder application and two without herder (reference ISBs). Burn of the oil slicks was anticipated to last approximately 10 minutes.

Sampling methods

Particles - $PM_{2.5}$

The particle fraction $PM_{2.5}$ was measured by SidePak™ Aerosol Monitor AM510 (Figure F.1), which is a real-time monitoring logging instrument weighing about 0.5kg. It has built-in impactors for 1.0, 2.5, 10-micron cut off sampling, and in this project the 2.5 micron impactor was selected and the logging interval was 1 second. Results are given as Time weighted average (TWA) in mg/m^3.

Figure F.1 SidePak™ Aerosol Monitor AM510 with built-in impactor for real-time monitoring of $PM_{2.5}$. (Photo: TSI)

PAH and "total" particulate fraction

PAH compounds are present as a combination of aerosol and vapour, and one standard method of air sampling is a "sampling train" which is a system that samples both aerosol and vapour of the relevant compounds (Figure F.2). This method consists of a combination of a 37mm closed-faced cassette with a teflonfilter /PTFE, 2 µm pore-size (SKC 225-1713) for sampling of aerosol/particles in the total particulate fraction in series with an adsorbent tube XAD2 (SKC 226-30-04) for sampling of the vapour fraction. The sampling cassette was attached to a pump with a recommended airflow rate of 2.0 l/min. Unfortunately, technical problems lead to sampling with an air flow of 0.2 liter/min which have increased the uncertainty of the measurements. The total weight of this sampling train was about 700g.

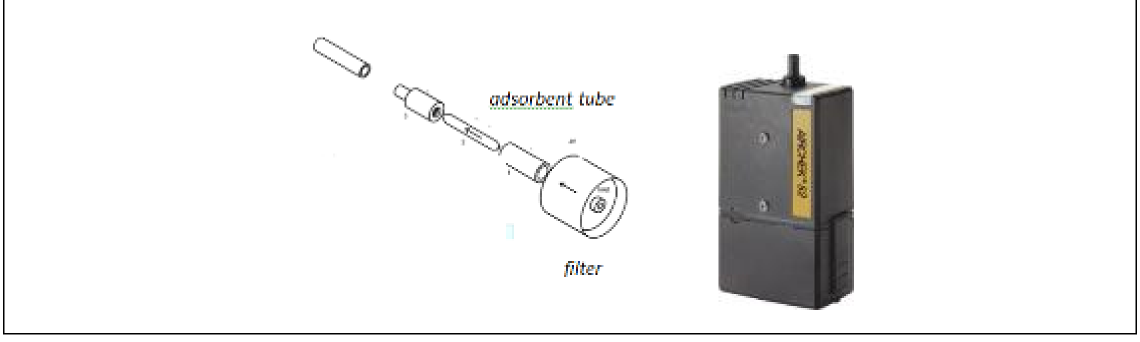


Figure F.2 Illustration of equipment for sampling of aerosol on filter and vapour on adsorbent tube (upper figure), and a sampling pump (lower figure). (The upper part of the figure is modified from STAMI, and the lower part taken from SKC).

Total particles on the Teflon filter was analysed gravimetrically (mg on filter; limit of detection 0.1 mg ±10%), and average air concentration (mg/m^3) was found by dividing by the air volume through the filter during the sampling period. The total particle fraction sampled by this method/sampling head does not have a defined cut-point for particle size. However, the sampler is widely used in US and Norway and resembles the inhalable sampler (50% cut-point=100 µm), but it underestimates the larger of the particles defined as inhalable.

21 PAH compounds (PAH21), in the particulate fraction and biphenyl and naphthalene in the vapour fraction) were desorbed from the filter and analysed by GC/MS, with detection limits of 0.1 µg/m^3 (±30%). PAHs were analysed according to NIOSH 5515, issue 2. Initially we also aimed for measurements of BTEX (benzene, toluene, ethylbenzene and xylene) on charcoal tubes. However, due to misunderstanding with the provider of the equipment, we were not able to sample these compounds.

Sampling locations (Table F.1).

1) Sampling in the smoke plume;
   One SidePak™ Aerosol Monitor was attached to a drone for continuous monitoring of $PM_{2.5}$ during three burning periods/oil slicks.
   The sampling equipment for PAH and total particles was also attached to this drone, for sampling during the three burning periods/oil slicks, one sample per burning period.
2) Sampling in the closest vessel- USV;
   One SidePak™ Aerosol Monitor for real-time monitoring of $PM_{2.5}$ was located in the manned USV
3) Sampling on drone operator located on Strilborg (Coastal Guard vessel)
   Sampling equipment for analysis of PAH and total particles was attached to the drone operator in the vessel during the three burning periods/oil slicks, one sample per burning period.

Table F.1 Sampling locations, instrumentation and analysis.

Location:	Within Smoke Plume	Upwind from the Smoke Plume – manned USV	Nearest Crosswind or Upwind Vessel (background data)
Sampling Platform:	Drone with sampling of total particle filter and PAH + Side Pak $PM_{2.5}$ particulate sampler	USV with Side Pak particle sampler	Sample pump and total particulate filter.
Parameters to measure:	Gravimetric analysis of total particle concentration (soot). PAH content of soot. $PM_{2.5}$ particles	$PM_{2.5}$ near sea surface	Gravimetric analysis of total particle concentration + PAH
Sampling Strategy:	Use a piloted quadcopter drone to obtain a smoke plume sample for at least 5 minutes within the smoke plume		Obtain background concentrations at deck location near the drone pilot.

The HSE plan precludes any manned vessel associated with this exercise from being downwind or under the smoke plume. The sampling drone was to remain within 600 meters of the pilot and had a set ceiling of 400 feet altitude.

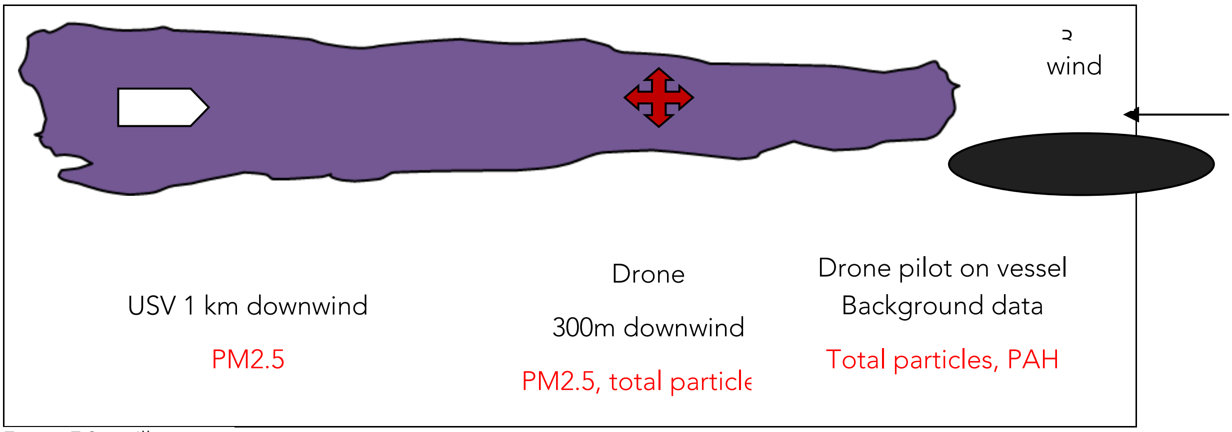


Figure F.3 Illustration

Air quality criteria and limit values

We refer to two sets of regulations, one for the general population and one for occupational exposure. The air quality criteria and limit values for the general population in always considerably lower than in occupational settings. For comparison reasons we have referred to these criteria and limit values also for samples taken in the smoke plume. However, we recognize that this is not relevant for human exposure as people are not located there, but stay on vessels upwind from the smoke plume.

The Norwegian Air Quality Criteria are established to protect the general population from adverse health effects. https://www.fhi.no/ml/miljo/luftforurensninger/luftkvalitetskriterier/

- The national criteria for $PM_{2.5}$ particles in air is 15 µg/m^3 (24 hours) and 8 µg/m^3 (annual average). The Limit Value for $PM_{2.5}$ particles in air is 25 µg/m^3 (annual average)
- Benzo[a]pyrene (B[a]P) is according to IARC a Group I carcinogen PAH, and is used as a marker for carcinogenic PAH in polluted air. The national criteria for B[a]P in air 0,1 ng/m^3 (annual average).

The Norwegian Occupational Exposure Limits (OEL) are set to protect workers from health risks from physical, chemical and biological factors and take into account, in addition to health considerations, also economical and practical aspects. http://www.arbeidstilsynet.no/binfil/download2.php?tid=252604

- The Norwegian OEL for the "total" dust fraction is 10 mg/m^3 (8 hour workday)
- Cancer is the critical health effects of PAH, and this is reflected in their low Occupational Exposure Limits (OELs)
  - OEL for particulate PAH (polyaromatic hydrocarbons) is 0.04mg/m^3(8 hour workday), and is based on the sum of 21 PAH-compounds;
  - *Anthracene, Benzo(a)anthracene, benzo[a]fluorene, benzo[b]fluorene, benzo[b]fluoranthene, benzo[j] fluoranthene, benzo[k]fluoranthene, Benzo[a]pyrene , Benzo[e]pyrene, benzo[ghi]perylene, dibenzo[a,h])anthracene, dibenzo[a,e]pyrene , dibenzo[a,h]pyrene, dibenzo[a,i]pyrene, dibenzo[a,l]pyrene, phenanthrene, fluoranthene, indeno((1,2,3-cd)pyrene, Chrysen, Pyrene and triphenylene.*

- OELs for biphenyl and naphtalene in the vapour phase are 1 mg/m^3 and 50mg/m^3, respectively.

Comments/calculations.

The upper measurement range for the SidePak™ Aerosol Monitor (PM2.5) is 20 mg/m^3. When the drone was in the smoke plume (4min, 4min and 7min for the three oil slicks) this upper measurement range was exceeded for several measurement points (96, 111 and 171 points for the three oil slicks) resulting in missing values for these points, which correspond to an equal number of seconds. When calculating the mean values for these periods, the upper range (20 mg/m^3) was used for these missing measurement points. Thus, for the time periods when the drone was in the plume our reported average $PM_{2.5}$ levels underestimate the actual levels of particles.

The limit of detection for total particles analyzed gravimetrically was 0.1 mg per filter. Due to the very short sampling times and the low air flow rate through the filters the amount of sampled particles/dust on the filters were below this lower limit for several of the samples, particularly for the drone operators. For filters with <0.1 mg, the particulate concentration (in mg/m^3) was not calculated, except from one filter that had 0.08 mg, i.e. close to this limit. These factors also have similar implications for the PAH-analysis. The limit of quantification of air concentration for these components is therefore considerably higher than when sampling for the recommended time of >100 min.

Results

Results from air measurements are presented separately for the three experiments 4.1, 4.2 and 4.3. **Part 1** presents results from the direct-reading instrument for $PM_{2.5}$ particles , while **Part 2** gives results from measurements of total particles and PAH.

PART 1: Results from monitoring of $PM_{2.5}$ with the *SidePak™* Aerosol Monitor

Experiment 4.1: 6 m^3 Grane Blend crude oil – June 14.

13:21 – 13:23	Release oil
13:53	Start herding
14:10 – 14:15	Start Ignition slick
14:14 – 14:28	Burning slick. Three separate burns in the slick for about 14 minutes
14:35 – 14:45	2nd burn takes place in the slick
15:00 – 15:30	Confinement of remaining residue

Table F.2 and Figure F.4a show that mean $PM_{2.5}$-levels in the USV were low. The highest level was during ignition of the slick (0.038 mg/m^3 for 6 min), while during the actual burning of the slick, the mean levels were low (0.006 and 0.012 mg/m^3) (Table F.2).

Measurements taken from the drone (Figure F.4b) showed very high levels when the drone was in the smoke plume (8.5 mg/m^3 for 4 min). In these 4 minutes, however, there were 96 sampling points (seconds) when the level exceeded the upper measurement range (20 mg/m^3), indicating that the actual level in the plume was higher than in Table F.2. When out of the plume the level dropped rapidly, and was similar to those in the USV, i.e. background levels.

Table F.2 Experiment 4.1; Results from monitoring of $PM_{2.5}$ by SidePak™ Aerosol Monitor.

			$PM_{2.5}$ (mg/m^3)			Figure
Time	min		AM	max	n>20 mg/m^3	
Measurements in USV						
13.15-13.45	30	Start Air monitoring until start herding	0.010	1.641	0	
14.09-14.15	6	Start Ignition of slick	0.038	0.689	0	4a
14.14-14.28	14	Burning slick	0.006	0.281	0	
14.35-14.45	10	2nd burn in the slick	0.012	0.209	0	
15.00-15.35	35	Confinement of residue	0.007	0.510	0	
Measurements from DRONE						
14.12-14.26	14	Burning slick – full period	2.5[a]	>20	96	4b
14.19-14.23	4	-Burning slick – when drone in smoke plume	8.5[a]	>20	96	
14.12-14.19& 14.23-14.26	10	-Burning slick – when drone not in smoke plume	0.025		0	

[a]Arithmetic mean is calculated by using 20 mg/m^3 for the 96 seconds when the upper measurement range was exceeded

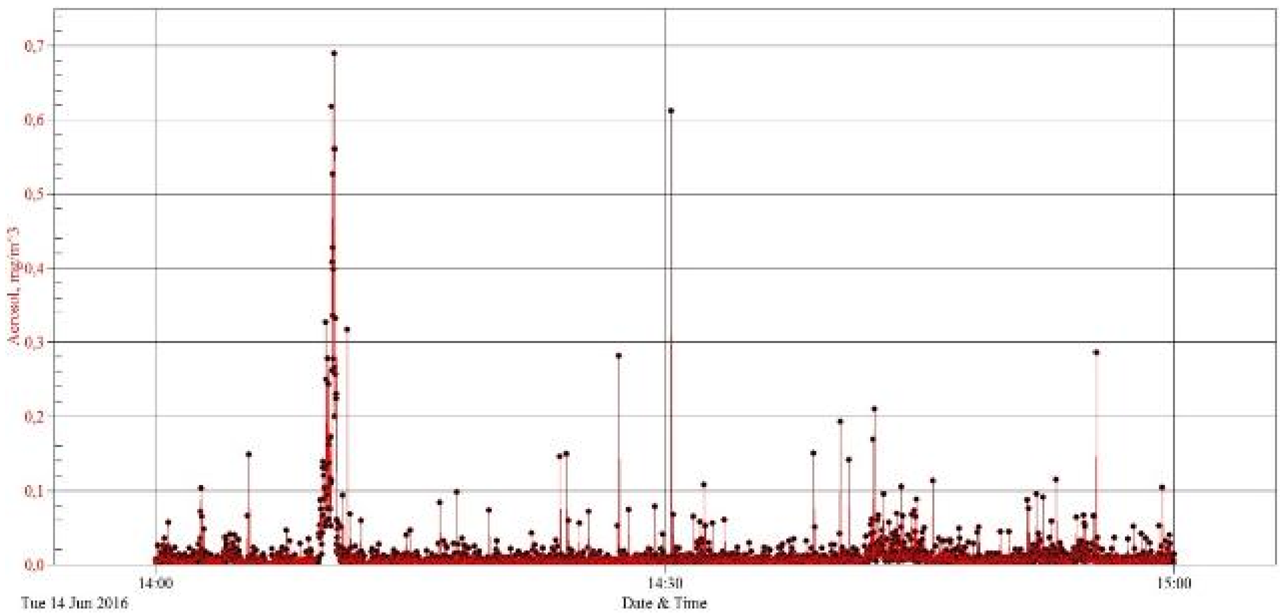


Figure F.4a Experiment 4.1- USV; $PM_{2.5}$ measured by SidePak™ Aerosol Monitor.

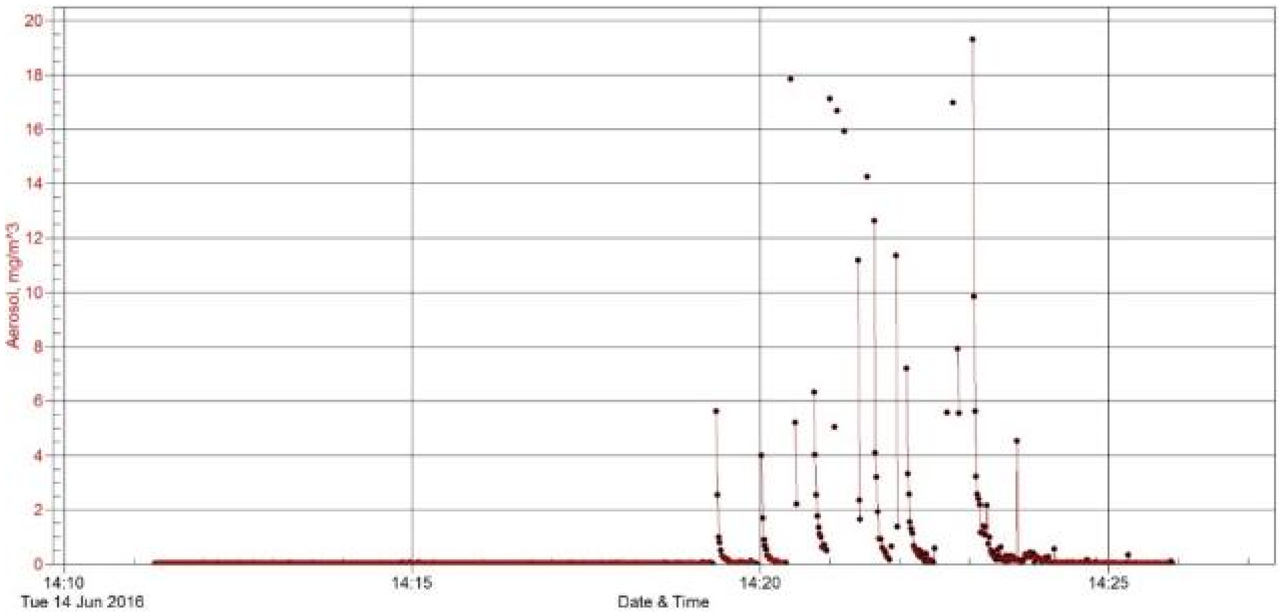


Figure F.4b ...Experiment 4.1- DRONE; $PM_{2.5}$ measured by SidePak™ Aerosol Monitor. (Note that the scale on the Y-axis is very different from Figure F.4a)

Experiment 4.2: 6 m^3 Grane Blend crude oil

15:40 – 15:43	Release oil (6 m^3 Grane Blend)
15:42 –:	Drones take off.
15:45 – 15:46	Water-flushing of Release tubes
16:33 – 16:35	MOB C splitting the slick, flare put in down-wind area
16:34: – 16:40	Main burn (in down-wind area). Duration approx. 6 min. before burn
17:00:	New flares. New ignition.
17:00 – 17:06	2nd burn
17:25 – 17:45	Application of dispersant

Table F.3 and Figure F.5a show that the mean $PM_{2.5}$-levels in the USV were low throughout Experiment 2, and quite similar to those reported for Experiment 1. Also in this experiment the highest level was during ignition of the slick (0.038 mg/m^3 for 5 min), while during the actual burning of the slick, the mean levels were low (0.007 and 0.008 mg/m^3) (Table F.3).

Measurements taken from the drone showed very high levels in the smoke plume (Figure F.5b; 10.8 mg/m^3 for 4 min). However, in these 4 minutes there were 111sampling points (seconds) exceeding the upper measurement range (20 mg/m^3), indicating that the actual level when the drone was in the plume was higher than shown in the table. When the drone was out of the plume the level dropped rapidly.

Table F.3 Experiment 4.2; Results from monitoring of $PM_{2.5}$ by SidePak™ Aerosol Monitor.

			$PM_{2.5}$ (mg/m^3)			Figure
Time	min		AM	max	n>20 mg/m^3	
Measurements in USV						
15.35-16.05	35	Start Air monitoring before ignition	0.008	0.427	0	
16.30-16.35	5	Flare put in	0.038	0.211	0	5a
16.34-16.41	7	Main burn	0.007	0.173	0	
17.00-17.10	10	Flare and 2nd burn	0.008	0.698	0	
17.25-17.39	14	Application of dispersant	0.011	0.190	0	
Measurements from DRONE						
17.02-17.08	6	Burning slick – full period	6.6[a]	>20	111	5b
17.03-17.07	4	-Burning slick – when drone in smoke plume	10.8[a]	>20	111	
17.02-17.03& 17.07-17.08	2	-Burning slick – when drone not in smoke plume	0.043		0	

[a]Arithmetic mean is calculated by using 20 mg/m^3 for the 96 seconds when the upper measurement range was exceeded

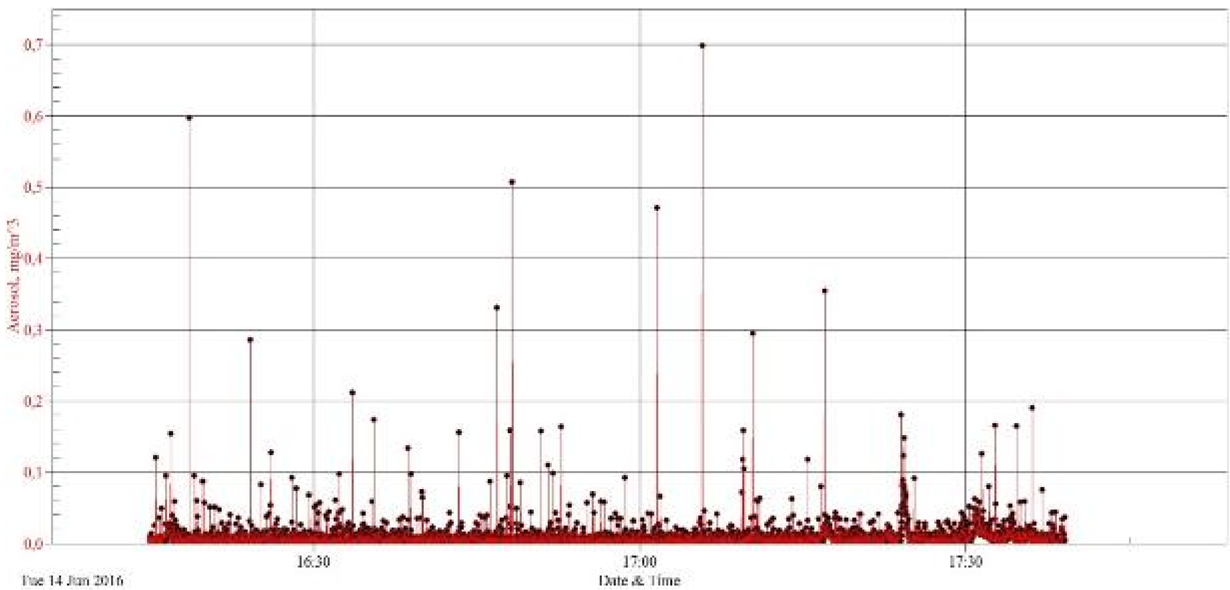


Figure F.5a Experiment 4.2- USV; $PM_{2.5}$ measured by SidePak™ Aerosol Monitor.

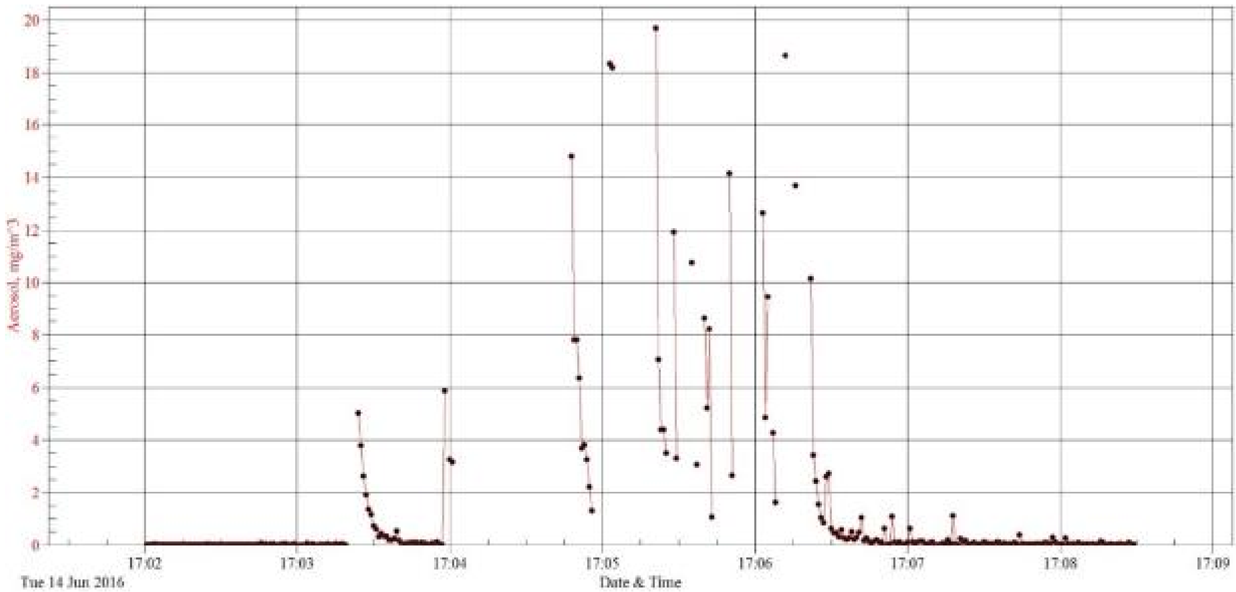


Figure F.5b Experiment 4.2- DRONE; $PM_{2.5}$ measured by SidePak™ Aerosol Monitor. (Note that the scale on the Y-axis is very different from Figure 5a)

<u>Experiment 4.3: 4 m^3 Grane Blend crude oil</u>

19:07 – 19:11 Release oil

19:40 – 19:50 Herding

19:51 – 19:54 1st Ignition- Difficult to ignite

19:57 – 19:59 2nd Ignition.

20:00: – 20:10 Main burn

20:10: – 20:15 Surface sampling

Table F.4 and Figure F.6 show very similar results compared to Experiments 1 and 2 when monitoring from the drone. The mean $PM_{2.5}$-level measured when the drone was in the smoke plume was 9.9 mg/m^3 for 7 min. In these 7 minutes there were 171sampling points (seconds) exceeding the upper measurement range (20 mg/m^3). When the drone was out of the plume the level dropped rapidly.

Table F.4 Experiment 4.3; Results from monitoring of $PM_{2.5}$ by SidePak™ Aerosol Monitor.

			$PM_{2.5}$ (mg/m^3)			Figure
Time	min		AM	max	n>20 mg/m^3	
Measurements in DRONE						
19.55-20.13	18	**Burning slick – full period**	3.8[a]	>20	171	6
20.02-20.09	7	-Burning slick – when drone in smoke plume	9.9[a]	>20	171	6
19.55-20.02& 20.09-20.13	11	-Burning slick – when drone not in smoke plume	0.038		0	6

[a]Arithmetic mean is calculated by using 20 mg/m^3 for the 96 seconds when the upper measurement range was exceeded

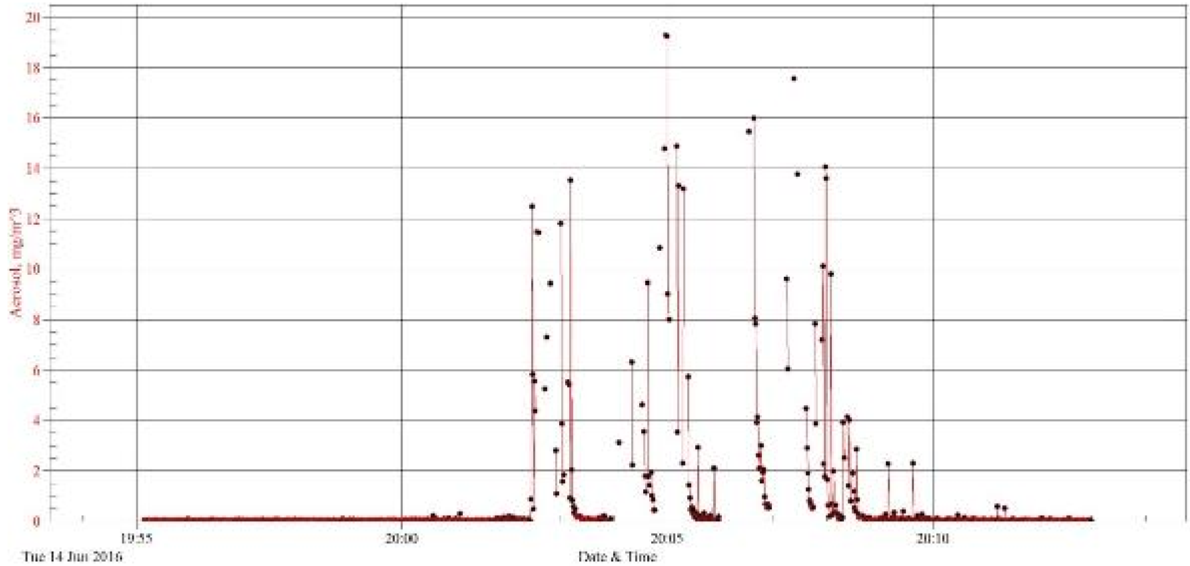


Figure F.6 Experiment 4.3- DRONE; $PM_{2.5}$ measured by SidePak™ Aerosol Monitor.

At the Newfoundland Offshore Burn Experiment (NOBE) burns the concentrations of particles (<3.0 μm) near the plumes was over 0.8-1.0 mg/m^3 near the fires, but decreased to about 0.1 mg/m^3 at 25 km downwind (Ross et al., 1996). The background particle concentration there was 0.030 mg/m^3.

PART 2: Results from air measurements of total particles and PAH on filter

Total particles

The total particle concentration was very high in two samples taken from the drone (Table F.5; 34.4 and 23.5 mg/m^3). These levels seem to correspond with the $PM_{2.5}$- levels measured from the same drone during burning of the same oil slicks (10.8 and 9.9 mg/m^3).

One should take into account that the drone was in the smoke plume for only about 4 and 7 minutes when these two samples were taken (as indicated by the $PM_{2.5}$ Aerosol Monitor recordings). **When assuming zero concentration when the drone was out of the smoke plume the total particle concentration in the smoke plume would be about 137 mg/m^3 and 57 mg/m^3 for sample 4 and 6, respectively (4 times and 2.4 times higher than those reported in Table F.5).**

This is comparable to the levels of total particulate matter reported in the smoke plume of a basin experiment oil burn by Booher & Janke (1997); 100-125 mg/m^3 in three experiments.

For the drone operators on Strilborg the particles mass sampled on the filter was under the limit of detection set by the laboratory, which is due to the short sampling time, the low air flow rate of the pumps, and the low concentrations.

Table F.5 *Results from gravimetric analysis of total particles in the three experiments.*

Sample ID		Time	min	Filter-weight after-before (mg)	Filter-weight corrected (-blind) (mg)	Reported by the lab (mg)	Air conc. (mg/m^3)
Experiment 4.1							
3	Drone 1	14.10-14.28	18	0.07	0.02	< 0.1	na[a]
7	Drone operator 1	14.15-14.36	21	0.08	0.03	< 0.1	na[a]
Experiment 4.2							
4	Drone 2	16.36-16.52	16	0.16	0.11	0.11	34.4[b]
5	Drone operator 2	16.36-17.20	44	0.09	0.04	< 0.1	na[a]
Experiment 4.3							
6	Drone 3	1955-20.12	17	0.13	0.08	< 0.1	23.5[cd]
2	Drone operator 3	19.00-20.15	75	0.11	0.06	< 0.1	na[a]

[a] Not calculated since weight on filter corrected for blind sample is considerably <0.1 mg

[b]Multiply the reported concentration with 4 for estimation of concentrations when the drone was actually in the smoke plume

[c]Concentration is calculated since the weight on filter corrected for blind sample (0.08 mg) is close to accepted value

[d]Multiply the reported concentration with 2.4 for estimation of concentrations when the drone was actually in the smoke plume

Polycyclic Aromatic Hydrocarbons (PAH) in the particle and vapour phases

For the two samples taken from drone 2 (sample 2) and drone 3 (sample 6) the 21 PAH components (PAH21) included in the Norwegian OEL were analysed on the Teflon filter. The sums of these 21 PAH components in these two samples were 2.3 and 12 $\mu g/m^3$ (Table F.6). The components with highest concentrations were phenantrene, anthracene, fluoranthene and pyrene. The concentration of benzo(a)pyrene, which is classified by IARC as certain carcinogenic for humans (IARC, group 1), was below the level of detection (<0.1 $\mu g/m^3$)

In the vapour fase of sample 2 and sample 6 both naphthalene (18 and 37 $\mu g/m^3$) and biphenyl (0.56 and 1.4 $\mu g/m^3$) were found in relatively low concentrations (Table F.6).

Table F.6 PAH-components in samples of vapour and total particles taken from the drone.

		Sample 4, drone 2[a] (sampling time 16 min- In smoke plume for 4 min)		Sample 6, drone 3[b] (sampling time 17 min- In smoke plume for 7 min)		Mean of sample 4 and 6
	PAH-compounds	PAH - vapour phase ($\mu g/m^3$)	PAH - particular ($\mu g/m^3$)	PAH in vapour phase ($\mu g/m^3$)	PAH - particular ($\mu g/m^3$)	PAH content in total particulates (µgPAH/g)
	Naphtalene	18	1.0	37	0.15	18
	Biphenyl	0.56	< 0.1	1.4	< 0.1	2
PAH21	Phenantrene	< 0.1	1.2	0.15	5.0	124
	Anthracene	< 0.1	< 0.1	< 0.1	0.1	3
	Fluoranthene	< 0.1	0.32	< 0.1	2.6	60
	Pyrene	< 0.1	0.12	0.1	3.3	72
	Benzo(a)fluorene	< 0.1	< 0.1	< 0.1	< 0.1	
	Benzo(b)fluorene	< 0.1	< 0.1	< 0.1	< 0.1	
	Benzanthracene	< 0.1	< 0.1	< 0.1	0.59	13
	Chrysene/Trifenylene	< 0.1	< 0.1	< 0.1	0.12	3
	Benzo(bjk)fluorantene	< 0.1	< 0.1	< 0.1	0.1	3
	Benzo(e)pyrene	< 0.1	< 0.1	< 0.1	< 0.1	
	Benzo(a)pyrene	< 0.1	< 0.1	< 0.1	< 0.1	
	Dibenzanthracene[c]	< 0.1	< 0.1	< 0.1	< 0.1	
	Indeno(1,2,3)pyrene[c]	< 0.1	< 0.1	< 0.1	< 0.1	
	Benzo(ghi)perylene[c]	< 0.1	< 0.1	< 0.1	< 0.1	
	Dibenzo(ah)pyrene[c]	< 0.1	< 0.1	< 0.1	< 0.1	
	Dibenzo(ae)pyrene	< 0.1	< 0.1	< 0.1	< 0.1	
	Dibenzo(ai)pyrene[c]	< 0.1	< 0.1	< 0.1	< 0.1	
	Dibenzo (al)pyrene[c]	< 0.1	< 0.1	< 0.1	< 0.1	
	ΣPAH21[d]	0.85	2.3	1.1	12	290

[a]Multiply the reported concentrations with 4 for estimation of concentrations when the drone was actually in the smoke plume

[b]Multiply the reported concentrations with 2.4 for estimation of concentrations when the drone was actually in the smoke plume

[c]50% uncertainty

[d]When the concentration of individual components is below the limit of detection (LOD), the LOD/2 was used in summing the concentration.

As indicated in the previous presentation one should also here take into account that the drone was in the smoke plume for only about 4 and 7 minutes when these two samples were taken. **When assuming zero concentration when out of the smoke plume the PAH concentration in the smoke plume would be about 4 times and 2.4 times higher than those reported in Table F.6 which is a Time Weighted Average value for the total sampling time for sample 4 (16 min) and 6 (17 min), respectively. Thus, when the drone was in the smoke plume the sums of the 21 PAH components for particulate PAH in the two analysed samples are estimated to be about 9 and 29 µg/m^3.**

Table F.6 also indicates the mean content of PAH in soot-particles in the two samples (in µg PAH/g). Such PAH compound ratios are commonly used as indicators of combustion source contributions to atmospheric pollution. *A recent article on particulate emissions from the Deepwater Horizon (DWH) oil burns (Gullett et al., 2016) showed that pyrene, fluoranthene, chrysene, and phenanthrene are among the PAHs with the highest concentrations in the soot, which is very similar to the results in the present project. This is also in agreement with a study of controlled oil burning in a basin by Booher & Janke (1997). Gullett et al (2016) has also compared such PAH "footprint" in particulate matter from different, previous oil burns and presented this information in a figure. They observed that PAHs in the DWH study were consistent with previous at-sea burn simulations albeit at lower concentrations. The concentration of PAH-components in particulate matter detected in our project, are within the range reported in the other studies, i.e. for most components somewhat higher than in the DWH burn, while lower than in some of the other oil burns such as Louisiana and Alberta crude oil in meso-scale (Evans et al., 2001, Fingas et al., 1996). However, there are many factors that contributes to the variability in measured PAH-content including type of oil, temperature, scale of experiment, sampling location, sampling method etc.*

Although also the air concentration measured in the smoke cloud will obviously vary with many factors, the PAH-component concentrations in the second sample in our study were quite similar to the ones found by Booher & Janke (1997) in the smoke plume of a basin experiment burn; phenanthrene (6.5 µg/m^3), pyrene (5.4 µg/m^3), fluoranthene (4.6 µg/m^3). In the mesoscale Mobile 1991 experiments the concentrations of three-ring PAH-components like phenanthrene and anthracene were higher in the smoke plume (Fingas et al., 1996) than in our study.

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Summary

Air measurements during three burning periods/oil slicks were taken at three locations for $PM_{2.5}$-particles, total particles and for PAHs in the total particle fraction and in the vapour phase; 1) In the smoke plume by a drone, 2) In the closest vessel- an USV and 3) On a drone operator located on deck on Strilborg (Coastal Guard vessel). Measurements in the smoke plume would provide us with the PAH "footprint" of the particulate PAH from the specific oil tested. The measured levels in the vessels would indicate the potential exposure level for humans in the vessels closest, but upwind to the smoke.
Main results;

- Measurements in USV;

  - Low mean concentration of $PM_{2.5}$-particles was found before and during burning (0.006-0.012 mg/m^3). The mean levels during burning were close to background concentrations before burning, and below the Norwegian Air Quality Criteria (0.015 mg/m^3 for 24h)
  - The highest levels were measured in the short period when the oil slick was ignited (0.038 mg/m^3).

- Measurements taken from the drone;

  - As expected the mean $PM_{2.5}$ levels were high in the smoke plume (>8.5-10.8 mg/m^3) when compared to the Norwegian Air Quality Criteria (0.015 mg/m^3 for 24h). The measured levels were more than 1000 times higher than the background concentration close to the coastal guard vessel. The continuous measurements showed that the $PM_{2.5}$ levels dropped rapidly when the drone went out of the smoke plume.
  - The total particle concentration (filter method) measured from the drone was very high (23.5-34.4 mg/m^3), which corresponds to estimated levels of 57-137 mg/m^3 when the drone was actually in the smoke plume (Norwegian OEL=10 mg/m^3).
  - The sum of the 21 particulate PAH components in the two analysed samples were 2.3 and 12 µg/m^3, which correspond to estimated levels of about 9 and 29 µg/m^3 in the smoke plume (Norwegian OEL=40 µg/m^3). The components with highest concentrations were phenantrene, anthracene, fluoranthene and pyrene. Benzo(a)pyrene, classified by IARC in Group1; certain carcinogenic for humans, was below the level of detection (<0.1 µg/m^3).
  - The concentration of PAH-components in particulate matter detected in our project (in µgPAH/g soot), are within the range reported for previous oil burns.
  - The PAH components in the vapour phase were found in low concentrations in the two samples (naphthalene: 18 and 37 µg/m^3 and biphenyl: 0.56 and 1.4 µg/m^3). (The Norwegian OELs are 50 mg/m^3 for naphthalene and 1 mg/m^3 for biphenyl)

- Measurements on drone operator located on the Coastal Guard vessel

  - The amount of sampled particles/dust on the filters on the drone operators were below the limit of detection (<0.1 mg), and was thus not analysed for PAH components.

Conclusions.

- As expected the concentrations of $PM_{2.5}$ particles and total particles were high in the smoke plume, by far exceeding the air quality criteria and limit values. The small $PM_{2.5}$-particles can be inhaled into the deepest part of the lungs, and are considered to be more hazardous than the larger particles.
- In the smoke plume PAH components, some of them carcinogenic, were detected in the particulate fractions of the air samples at levels approaching the Norwegian OEL. The PAH "footprint" was comparable to previous oil burns, particularly the DWH-spill/burn. In the vapour phase of the smoke plume, PAH components were detected at low concentrations.
- The levels of $PM_{2.5}$ particles declined rapidly when the drone left the smoke plume, and were low both in the USV and the Coastal Guard vessel, i.e. below the Norwegian criteria for air quality for the general population. The $PM_{2.5}$ levels were low in these vessels also during the actual burning process.
- Particulate PAH is bound to the soot-particles. Thus, the PAH-concentration will decrease similarly as reported for the particles when moving away from the smoke plume. PAH was below the limit of detection in the USV and the Coastal Guard vessel.
- The short sampling times due to the short burning process, and the low air flow rate through the filters generally led to a low amount of sampled particles/dust/PAH on the filters, and have increased the uncertainty of filter measurements (total particles and PAH-component profiles).
- Nevertheless, the results strongly indicate that on the vessels placed upwind from the smoke plume, human exposure to hazardous compounds from the actual burning process was very low/negligible.

References

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APPENDIX G ESTIMATION OF BURN EFFECTIVENESS BY INTEGRATED TIME-AREA (ITA) APPROACH

Burn volumes for Test 1, Test 2, and Test 3 was estimated using an integrated time-area approach. Aerial imagery was employed with analysis techniques to determine the enflamed surface area. Due to the presence of smoke and the three-dimensional nature of the flames more than one image from different perspectives is required to estimate flame area.

Two additional methodologies were considered, but ultimately rejected as explained below. The three approaches are:

Gravimetric Method

This method of calculating burn efficiency relies on the ratio of the mass of oil burned to the initial oil mass. The following equation may be used to calculate the overall efficiency for a burn:

$$\text{Overall Burn Efficiency (mass \%)} = \frac{\text{(Initial Oil Net Weight - Residue Net Weight) x 100\%}}{\text{Initial Oil Net Weight}} \quad (1)$$

Residue would either be assumed to be water free, or an emulsion breaking agent would be applied to the recovered fluid, and any water recovered would be separated out. Uncertainties arise from the inherent assumptions applied to this method. The first is the assumption that all mass loss is resulting from burning, not from other factors such as dissolution of soluble components of the oil or evaporation of the volatile components. Second, this method assumes that all remaining oil and residue following the burn is retrieved and weighed.

This method was rejected at the outset due the logistical difficulty in ensuring all of the residue would be recovered.

Maximum Burn Area (MBA) Approach

In this approach, the maximum burn area is determined, then multiplied by the assumed burn rate and the duration of time over which more than 50% of the maximum burn area is aflame. This is mathematically described as:

$$MBA\ Burn\ Volume = Burn\ Rate\ x\ Maximum\ Flame\ Area\ x\ (E_{50} - I_{50}) \quad (2)$$

Where E_{50} represents the time at which the burn area diminishes to half its maximum area (extinction half-time), and I_{50} represents the time at which the spreading burn reaches half its maximum area (ignition half-time).

This method was tentatively rejected due to the incomplete video and photographic coverage that was available for analysis to determine an actual maximum area.

Integrated Time-Area (ITA) Approach

In this approach, the flame area integrated over the duration of the burn is multiplied by an assumed burn rate. In this instance, the burn rate of fresh Grane crude as assumed to be a conservative 3.0 mm/min, based upon an estimated minimum starting 3 to 4 mm slick thickness:

$$ITA\ Burn\ Volume = Burn\ Rate\ \int_0^t Flame\ Area\ (dt) \quad (3)$$

Note that the ITA an approach produce estimates only, due to uncertainties associated not only with interpretation of the aerial imagery, but also associated with the assumed burn rate of 3.0

mm/min. A value of 3.5 mm/min is often assigned to be the burn rate for open water slicks as long as the slicks are thick enough to minimize heat loss back to the water column. A review of available data for slicks less than 10 mm thick indicates a slight decline in overall burn rate of about 10% with a decline in slick thickness from 10 mm to 5 mm, with a further reduction in burn rate for slicks down to 2 mm thickness (In Situ Burning in Ice-Affected Waters: State of Knowledge Report, Final Report 7.1.1 – Buist et al. 2014)

Test 1 (Experiment 4.1): 6 m3 Grane Blend crude oil, use of 4.9 L herder.

Figure G.1below shows the burn data collected during the first portion of the test, which is comprised of two separate burns that occurred with some overlap. Flame area was calculated based upon and analysis of the combined areas of the burns over the prescribed time period. The combined burning lasted approximately 15 minutes.

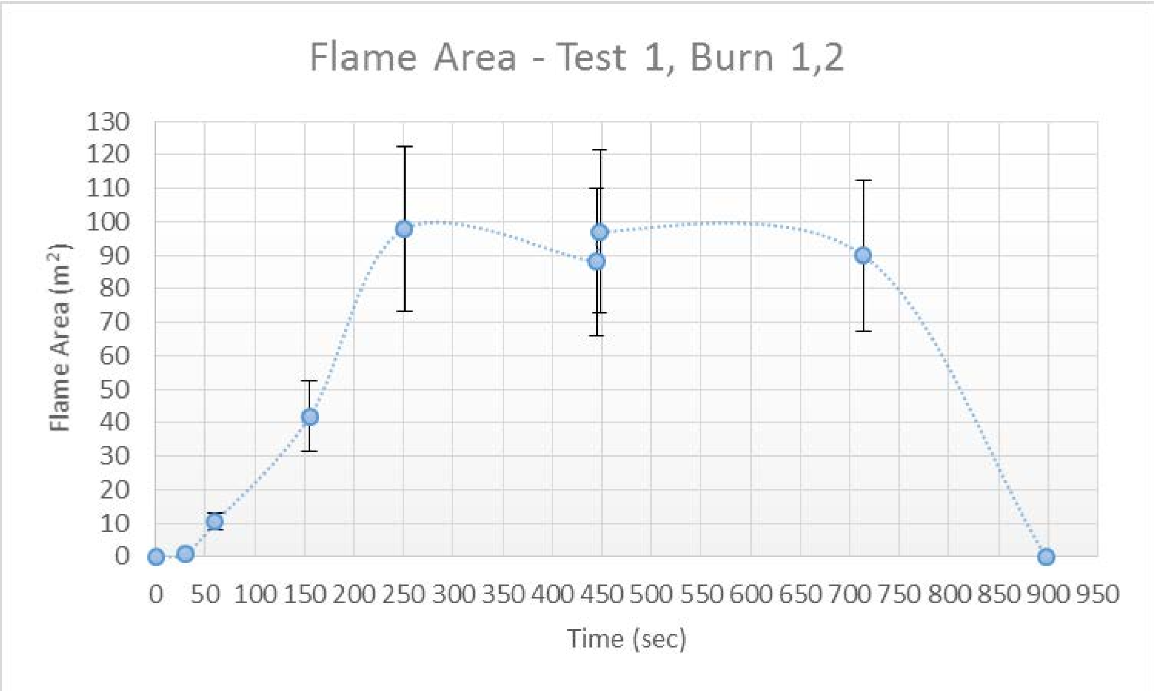

Figure G.1 Flame area for Test 1, Burn 1 and 2

Error bars of 25% have been used and are representative of the difficulties in analyzing the photos and video captured during all runs. The 25% represents errors in tilting and de-skewing the photographs and the inclusion of limited scaling items for photographic correction and inaccuracy in burn regression rate estimates.

Using equation 3 identified above with an area-time integration of 64,000 m^2s gives an oil volume burned estimate of 3200 L.

The next figure shows the burn data collected for a third burn which occurred at the end of Test 1. This was a smaller burn that lasted approximately 5 minutes long.

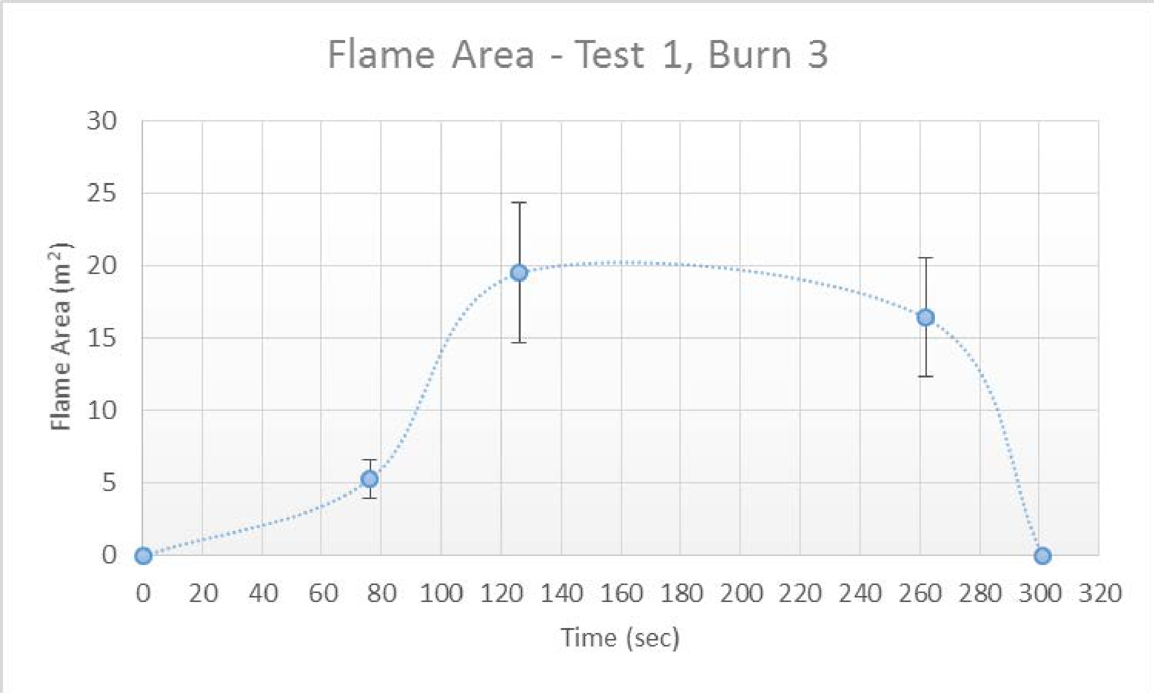

Figure G.2 Flame area for Test 1, Burn 3

Using equation 3 to generate an area-time integration of 3800 m^2s gives an oil volume burned estimate of 190 L.

Combined these burns account for 55% of the estimated 6 m^3 of oil that was initially released, as shown below in Table G.1.

Table G.1 Test 1, 6 m^3 Grane Blend crude oil burn

	m2.s	mm/min	m/mm	min/s	volume (m^3)	volume (L)	% consumed (rounded to nearest 5)
BURN 1, 2	64000	3	0.001	0.016667	3.2	3200	
BURN 3	3800	3	0.001	0.016667	0.19	190	
COMBINED					3.39	3390	55

Test 2 (Experiment 4.2): 6 m^3 Grane Blend crude oil, no herder.

Figure G.3 shows the burn data collected during the first portion of Test 2, which is also comprised of two separate burns that occurred with some overlap. Flame area was calculated based upon and analysis of the combined areas of the burns over the prescribed time period. The combined burning lasted approximately 6 minutes.

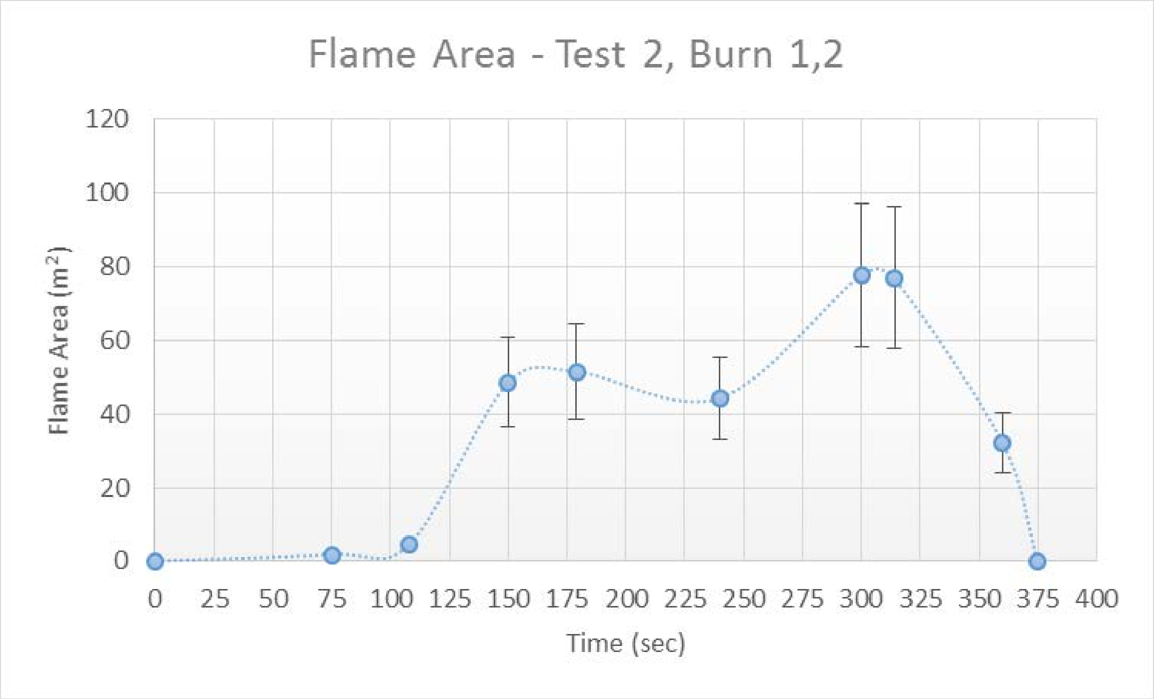

Figure G.3 Flame area for Test 2, Burn 1 and 2

Using equation 3 identified above with an area-time integration of 13150 m^2s gives an oil volume burned estimate of 658 L.

The next figure shows the burn data collected for the last burn of Test 2. This burn lasted just over 7.5 minutes long.

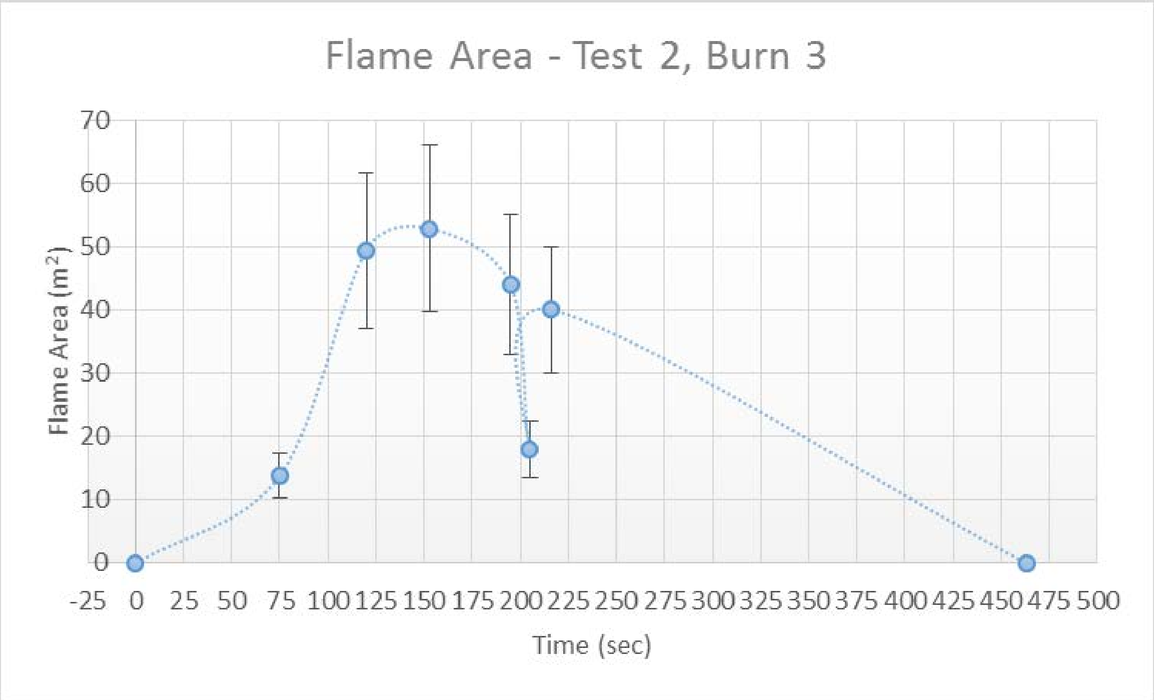

Figure G.4 Flame area for Test 2, Burn 3

Using equation 3 to generate an area-time integration of 11375 m^2s gives an oil volume burned estimate of 569 L.

When combined these three burns account for approximately 20% of the estimated 6 m^3 of released oil. Summary data is provided below in Table G.2.

Table G.1 Test 2, 6 m^3 Grane Blend crude oil burn

	m2.s	mm/min	m/mm	min/s	volume (m^3)	volume (L)	% consumed (rounded to nearest 5)
BURN 1, 2	13150	3	0.001	0.016667	0.66	658	
BURN 3	11375	3	0.001	0.016667	0.57	569	
COMBINED					1.23	1226	20

Test 3 (Experiment 4.3) 4 m^3 Grane Blend crude oil, 6.4 L herder.

Figure G.5 below shows the burn data collected during Test 3. Flame area was calculated based upon and analysis of area of the burn at intervals over the prescribed time period. The combined burning lasted approximately 8 minutes.

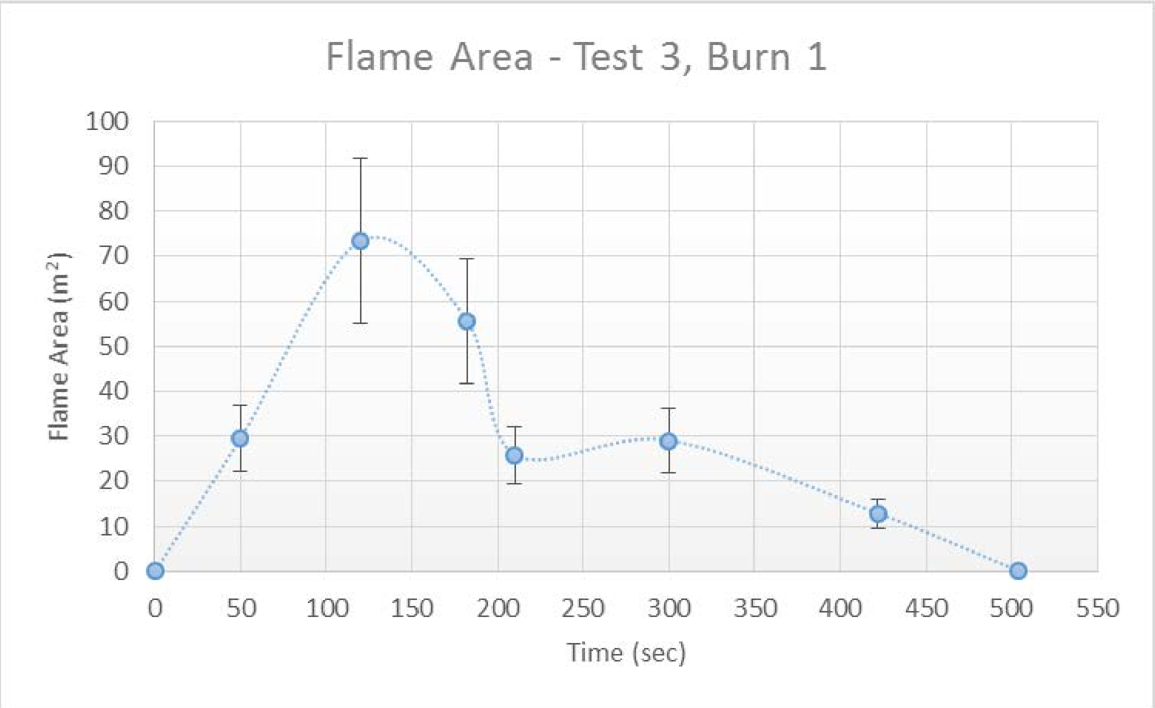

Figure G.5 Flame area for Test 3, Burn 1

Using equation 3 to generate an area-time integration of 15400 m^2s gives an oil volume burned estimate of 770 L of the estimated 4 m^3 of released oil.

Table G.3 Test 2, 4 m³ Grane Blend crude oil burn

	m2.s	mm/min	m/mm	min/s	volume (m³)	volume (L)	% consumed (rounded to nearest 5)
BURN 1	15400	3	0.001	0.016667	0.77	770	20

<u>Summary of Burn Efficiencies</u>

	volume (m³)	volume (L)	% consumed (rounded to nearest 5)	Burn efficiency range, %
TEST 1	3.39	3390	55	30 to 80
TEST 2	1.23	1226	20	Up to 45%
TEST 3	0.77	770	20	Up to 45%