Experiments at Sea with Herders and In Situ Burning (HISB)

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ABSTRACT

A series of experiments involving herders and ISB (designated HISB) were conducted at sea on 14th – 15th June 2016, near the Frigg Field in the North Sea. The primary objective of the experiments described in this paper was to demonstrate, at near-full scale, the use of herders followed by in situ burning (ISB) in open water conditions and validate the findings of an earlier field study of herders in conjunction with ISB. Two experimental releases of 6 m^3 (approximately 40 barrels) and one of 4 m^3 of Grane Blend crude oil were undertaken. The released oil spread out differently on the sea surface in each of the slicks due to slight variations in release conditions and prevailing wind conditions. Herder (ThickSlick 6535) was applied around two of the slicks by spraying from a small boat; a third slick was not herded before ignition. In the first test, approximately 80% of the total amount of thick oil was herded to form a coherent slick with an average oil layer thickness of approximately 3 mm to 5 mm. The second herded slick accounted for 40% of the amount of oil released and resulted in an average layer thickness of approximately 2 mm to 3 mm present as several discrete areas of thick oil. The average oil layer thickness in the non-herded slick was 2.5 mm to 3 mm (under very calm weather conditions) and this slick had also been broken up into several discrete areas of thick oil.

Ignition with gelled gasoline igniters was carried out approximately one hour after oil release. All three slicks were successfully ignited. Approximately 3.4 m^3 of the available oil in the

first herded slick was consumed in three distinct burns, while the second herded slick consumed 0.8 m^3 of oil in only one burn. The remaining test involving an unherded slick consumed approximately 1.2 m^3 of oil in three burns.

INTRODUCTION AND BACKGROUND

Herders are surfactants that have a spreading pressure 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. Small-scale laboratory experiments were completed in 2003 and 2005 (SL Ross 2004, 2005) to examine the concept of using herding agents to thicken oil slicks among drift ice for the purpose of In Situ Burning (ISB). Encouraging results prompted further 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). Successful mid-scale field trials of the technique involving 0.6 m^3 of Heidrun crude 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). 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;
- 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.

Additional details on these earlier experiments may be found at:

http://www.arcticresponsetechnology.org/wp-content/uploads/2015/05/Herder-Research-Summary.pdf

OBJECTIVE

The primary objective of the experiments described in this paper 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.

METHODS

Overview

A series of experiments with herders and ISB (designated HISB) were conducted at sea on 14^{th} -15^{th} June 2016, near the Frigg Field in the North Sea. The location is approximately 140 miles (230 kilometres) north-west of Stavanger where the ships were based. The experiments were part of the NOFO (Norwegian Clean Seas Association for Operating Companies) Oil-On-Water field trial (OPV - Olje pa Vann - 2016). Two experimental releases of 6 m^3 (approximately 40 barrels) and one of 4 m^3 of Grane Blend crude oil were undertaken. Herder (ThickSlick 6535) was applied around two of the experimental slicks using hand-held pressurized sprayers from a small boat; a third slick was not herded. Ignition with gelled gasoline igniters was carried out approximately one hour after oil release.

Organisations involved

NOFO had overall responsibility for arranging the vessels, remote sensing aircraft, permits and funding of experiments. SINTEF was responsible for administering the various sub-contractors, including SL Ross and Maritime Robotics and provided personnel for the experimental programme. SL Ross directed each individual experiment and analysed the available data with the assistance of Alun Lewis Consultancy. The HISB experiments were funded by The International Association of Oil & Gas Operators (IOGP) - Arctic Oil Spill Response Technology Joint Industry Programme.

Equipment and personnel involved

Two vessels were provided by the Norwegian Coastal Administration (NCA) and the Norwegian Coast Guard (Kystvakten):

- KV Sortland was responsible for the oil releases for the HISB experiments. An unmanned surface vessel (USV) with an Aerostat (OceanEye® with visual and IR video cameras) from Maritime Robotics were stationed and launched from KV Sortland.
- MS Strilborg is a supply and response vessel, under contract for NCA as an emergency tow-vessel. Two MOB (Man Over Board) boats were used for sampling, the herding and ignition operations, and in containment and recovery of burn residue.

Surveillance aircraft were provided by the NCA, Finnish Border Guard/SYKE and the Netherlands Coastguard. These aircraft are equipped with SLAR (Side Looking Airborne Radar), EO/IR (Electro Optical / IR) known also as a FLIR (Forward Looking Infra-Red) and the Finnish aircraft also had an IR / UV line scanner. Maritime Robotics of Trondheim, Norway provided quadcopter drones with HD video, an air sampling drone, and operators.

Oil used

Grane Blend is a heavy, high Total Acid Number (TAN) and asphaltenic crude oil, produced from the Grane, Svalin and the Edvard Grieg fields in the North Sea. SINTEF conducted a laboratory weathering study on this oil. In the low wind speeds required for the experiments to proceed, the Grane Blend crude oil was predicted to lose approximately 5% volume by evaporation, not to form water-in-oil emulsions and the pour point of the lightly weathered oil residue would be at least 10°C below the prevailing sea temperature.

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

Table 1. Grane Blend 2016 Oil Properties

EXPERIMENTS

Experiment 1 (HISB 4.1: Herd and burn)

Six cubic metres of Grane Blend crude oil was released onto the sea surface from KV Sortland at 13:21 to 13:23 Local Time (LT), (UTC+2:00), over a distance of 50 to 80 metres. The winds were 3 - 4 m/s from the NNE and the sea was calm with no breaking waves. The oil spread out and 4.9 litres of herder was applied using hand-held sprayers from a MOB boat around the slick after it had been on the sea for 30 minutes. Due to various operational issues, no aerial images of the slick were taken prior to herding. Figure 1 shows herding completed.

Figure 1 Photo of HISB 4.1 slick (Netherlands Coast Guard)

The herded thick oil is easily 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 1). The area of the herded oil was estimated to be 1,250 m^2 with an error of $\pm$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, the average oil layer thickness in the herded area was approximately 3.2 mm to 4.8 mm.

Three igniters (marine flares with gelled gasoline and supplemental flotation) were added to the HISB 4.1 slick 50 minutes after the oil was released and 15 minutes after the herder had been applied. The oil caught fire and the burn intensity rapidly increased (Figure 2). The initial burn lasted for 14 minutes.

Figure 2. *Intense burn in HISB 4.1 slick*

A second burn lasted for 5 minutes, while a third burn lasted an additional 5 minutes.

Experiment 2 (HISB 4.2; Reference slick. Monitor and burn, no herder)

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 (Figure 3).

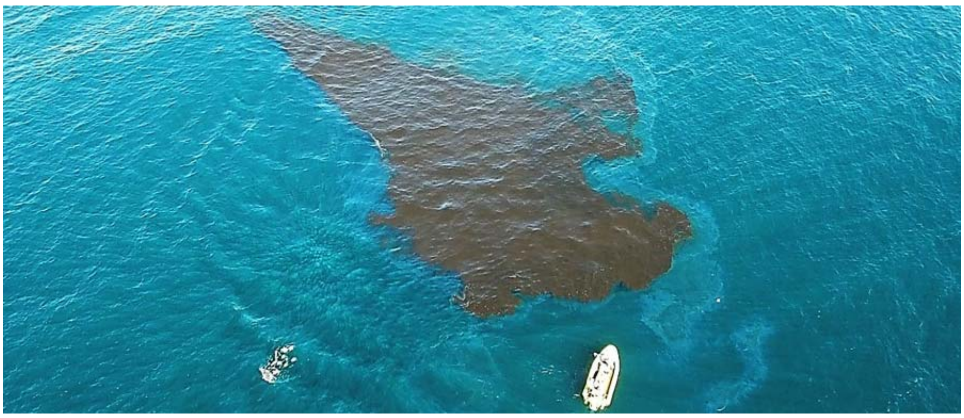

Figure 3. *HISB 4.2 slick with compact area of thick oil surrounded by sheen*

In the very calm conditions the slick did not drift far and remained compact (a maximum of 90 metres long and 35 metres wide) with some sheen around it (Figure 3).

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. Image analysis estimated the area of thick oil in the HISB 4.2 slick to be 2,150 m^2 ($\pm$10%, giving 2,000 m^2 to 2,350 m^2 as the likely range). The average thick oil layer thickness for 6m^3 of oil was calculated to be 2.5 mm to 3.0 mm and this agreed well with measurements made by a technique using sorbent pads for quantitative sampling over discrete areas to determine manual measurements of oil thickness. 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. However, 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 4 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.

Figure 4. HISB 4.2 slick just as igniters were deployed 14:34 UTC (16:34 LT)

An igniter was deployed from the MOB boat 50 minutes after the oil had been released onto the sea surface and a second igniter was added one minute later (Figure 5).

Figure 5. Ignition of HISB 4.2 slick time 14:35 UTC (16:35 LT)

The initial burn lasted for approximately 3 minutes while the second burn continued (Figure 6) for 5 minutes.

Figure 6. Intense burn in part of HISB 4.2 slick at 14:38 LT (16:38 UTC)

Figure 7 is a still from the HDIR video taken at 14:41 UTC (16:41 LT) after the initial burns had ended.

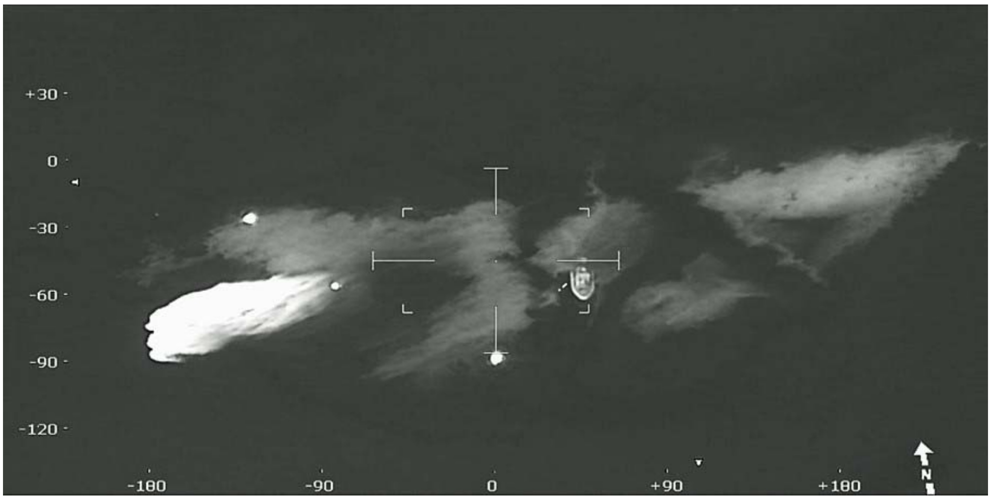

Figure 7. HISB 4.2 slick just before igniters were deployed 14:41 UTC (16:41 LT)

The area of the thick oil in the slick where the burns had taken place shows up as a brighter white because the residue remaining after the burn is still very warm. It can be seen that the first burn was confined to just one of the separated thick oil patches. 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. There was a pause while extra igniters were prepared. The third burn was ignited 80 minutes after oil release and lasted for 8 minutes.

Experiment 3 (HISB 4.3)

Four cubic metres of Grane Blend crude oil was released onto the sea surface from KV Sortland at 19:08 to 19:11 LT. The wind had increased to 5 m/s from NNE and there were slightly rougher seas, with occasional breaking waves. 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. This still from the drone video (and Figures 9 and 10) has had colour saturation increased to 200% to make the difference appearance of the areas of different oil thickness more apparent.

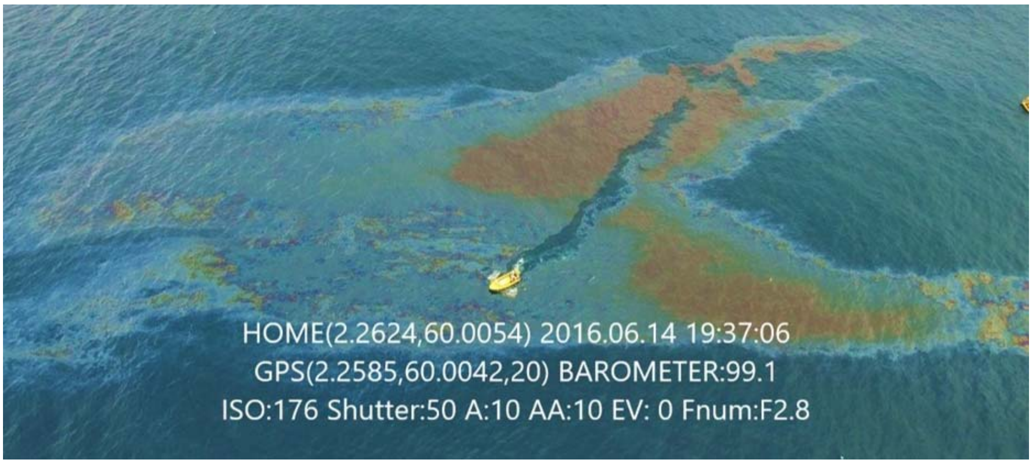

Figure 8. *HISB 4.3 slick at the start of herding.*

The most coloured area of slick in this enhanced image is the thick oil and the areas of thinner sheens can also be seen. Image analysis was used to subdivide the estimated total slick area of the known volume of oil into 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 BAOAC is routinely used by maritime surveillance aircraft crews in Europe on their regular pollution patrols. Unlike these patrols which seek to quantify the amount of oil on the sea surface, in these experiments the volume of oil on the sea (and adjusted for evaporative loss) was known. The results of this analysis are presented in Table 2.

BAOAC (Bonn Agreement Oil Appearance Correlation)			**HISB 4.3 in Figure 5**			
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**		

Table 2. *BAOAC analysis of HISB 4.3 slick in Figure 9*

The total area of the slick was approximately 11,200 m^2. With an estimated accuracy of ±15% the total slick area was between 9,500 m^2 and 12,900 m^2. The area of the thick (CTC) oil was around 3,500 m^2, 30% of the total slick area. This is still larger than the thick oil area in the HISB 4.2 slick which was 2,150 m^2. Even though the HISB 4.3 slick was of 4 m^3 of Grane Blend oil, compared to the 6 m^3 of the same oil in slicks HISB 4.1 and 4.2, the HISB 4.3 slick was considerably bigger. This is because the slick had drifted with the low speed wind. This drifting produced a large area of sheen, rainbow sheen and metallic appearance 'behind' the drifting thick oil, but also caused the thick (CTC) oil to spread out more and thus become thinner. 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.

As is illustrated in Figure 9, the MOB boat applied herder (shown as a broken yellow line) around only a section of the slick and the herded area included thick oil, but also some area of the thinner oil. A total of 6.4 litres of herder was sprayed over a 7 minutes period. 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 1.4 m^3 of oil was herded, while 60% of the thick oil area containing around 2.2 m^3 of oil was not herded. The herded rainbow sheen and metallic appearance oil was rapidly contracted within 2 or 3 minutes "inwards" towards the thick (CTC) oil (yellow arrows), but also herded the thinner oil "outwards" (red arrows).

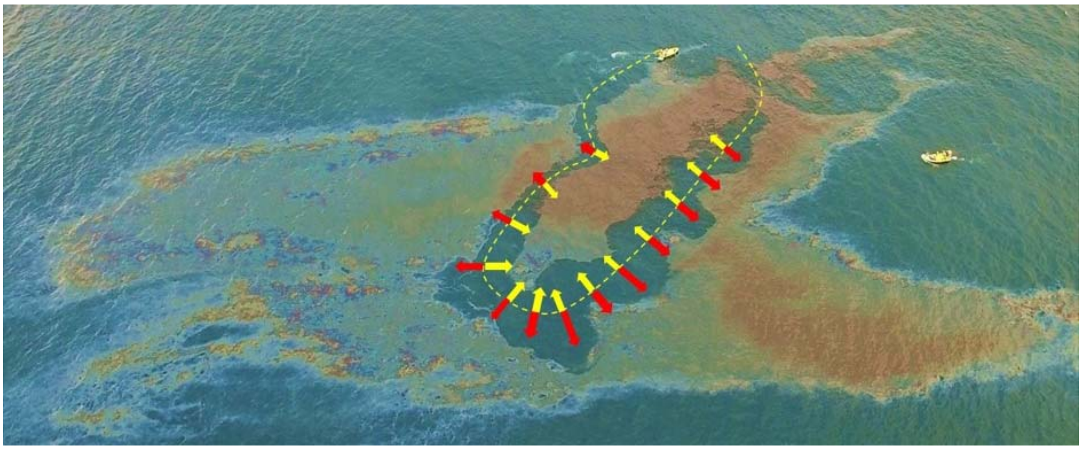

Figure 9. Herding of HISB 4.3 slick

The increase in the width of the clear water gap was due to both of these effects. 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 or 3 mm (Figure 10).

Figure 10. Fragmented areas of herded HISB 4.3 slick

The herded area had become fragmented in three separate areas. Igniters were deployed and the oil was ignited (Figure 11).

Figure 11. Ignition of herded portion of HISB 4.3 slick

RESULTS AND DISCUSSION

The three HISB experiments at sea were all conducted in one day over a period of 7 hours. The same 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.

A. Spreading of oil

a. HISB 4.1. 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. No aerial images exist of the HISB 4.1 slick before herding, so no accurate estimates of the slick area (and therefore oil layer thickness) can be made. However, the image obtained from the Netherlands surveillance aircraft after herding was completed (Figure 5) indicates approximately the area that the oil had previously spread before herding. The same image is reproduced as Figure 12 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 3,500 m^2 to 5,000 m^2 and probably had an average oil layer thickness of approximately 1.2 mm to 1.7 mm before herding. In the absence of relevant images no better oil area estimate can be made.

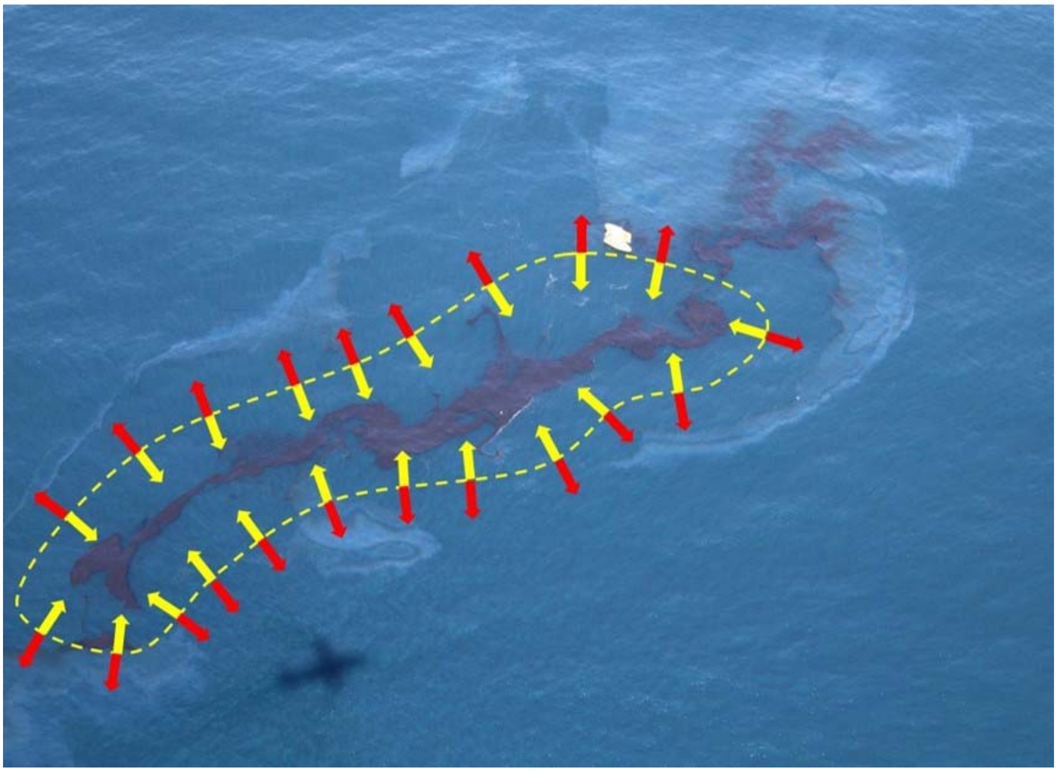

Figure 12. Probable area of oil HISB 4.1 slick before herding

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. No herder was applied around slick HISB 4.2. 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 2350 m^2) and unexpectedly maintained an average oil layer thickness of 2.5 mm to 3.0 mm.

c. HISB 4.3. The $4m^3$ of oil released to form the HISB 4.3 slick was initially released as a compact slick, but drifted in the slightly 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 thinner layer.

As shown in Table 2, the total area of the HISB 4.3 slick before herding was estimated at 11,200 m^2, but only 30% (3,500 m^2) of this was thick oil. The thick oil area of the slick had an average oil layer thickness of approximately 1.1 mm before herding.

Although no herder was applied to the HISB 4.2 slick, it had a higher average oil thickness in the thick oil area than in HISB 4.1 and HISB 4.3 slicks before they were herded. This is because the HISB 4.2 slick was released as a slightly more compact slick and it did not drift appreciably in the very low prevailing wind speed.

One of the 'rules of thumb' about ISB is 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). Thinner oil layers lose too much heat to the underlying water to sustain the vaporisation of the flammable components from the oil by the heat from the flames that is essential for burning to be sustained. The effectiveness of ISB is directly related to the thickness of the burning slick. The oil used in these experiments was a very lightly weathered 'fresh' crude oil and therefore would be likely to burn, but the average oil layer thicknesses of approximately 1.2 mm to 1.7 mm in the HISB 4.1 slick and of approximately 1.1 mm in the HISB 4.3 slick before herding made sustained, effective burning unlikely. The greater average oil layer thickness of 2.5 mm to 3.0 mm in the HISB 4.2 slick, as a result of the very calm conditions, was not anticipated and influenced the outcome of the experiment.

B. 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. Herding increased the average oil thickness from probably 1.2 mm to 1.7 mm before herding to 3.2 mm to 4.8 mm just before ignition.

b. **HISB 4.2**. No herder was applied to the HISB 4.2 slick and the average oil thickness before ignition was 2.5 mm to 3.0 mm. Repeated transits by MOB boats through the thick oil area in the HISB 4.2 slick had broken the thick oil into a few discrete patches.

c. **HISB 4.3**. Only 1,500 m^2 (40% of the total) of the thick oil area present in slick HISB 4.3 was herded. The herded area of thick oil became fragmented into three smaller patches that were progressively contracted by the herder. The average oil thickness increased from approximately 1 mm before herding to 2 mm or 3 mm after herding. See Figure 13.

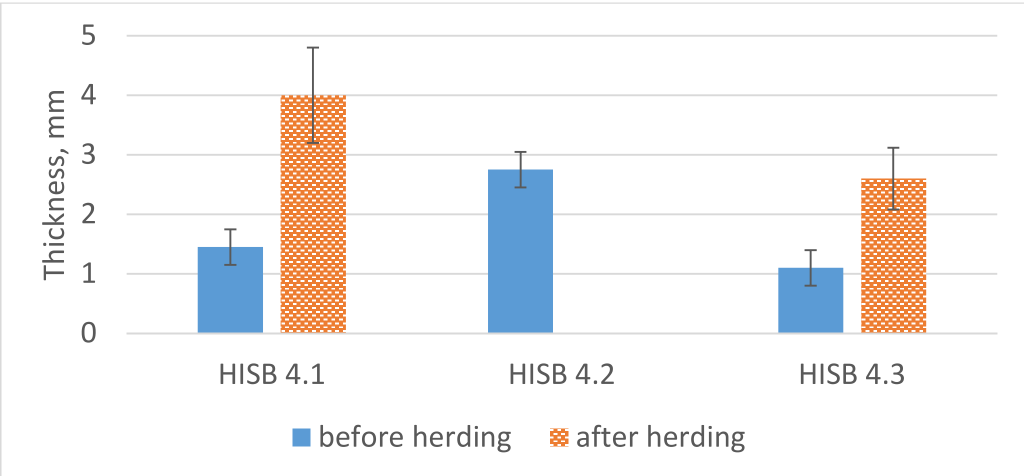

Figure 13. Estimated average thickness of thick oil portion of slicks

The average oil layer thickness of the thick oil in the two slicks that were herded, HISB 4.1 and 4.3, increased substantially as a result of the herding.

C. Ignition and burning of oil

a. **HISB 4.1**. Three ignitions were attempted in the herded HISB 4.1 slick and all were successful. With some overlap in the burns, the overall burn duration was 20 minutes.

b. **HISB 4.2** Three burns were ignited in the non-herded HISB 4.2 slick with eight ignitions attempted. The third burn was ignited 80 minutes after oil release. The overall burn duration was 13 minutes.

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

All three experimental slicks, both the herded slicks (HISB 4.1 and 4.3) and the non-herded HISB 4.2 slick were successfully ignited and sustained burning occurred.

The videos from the quadcopter drones were analysed using the Integrated Time-Area approach 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 $\pm$25% error. This error margin was due to limited availability of appropriate images and the inclusion of limited scaling items for photographic correction. The burn rate of fresh Grane Blend crude oil was assumed to be 3 mm/min, based upon a review of known burn rates (Buist et al., 2014).

On this basis, the amount of oil burned in each slick and the estimated proportion of oil burned was estimated to be:

a. **HISB 4.1**: 3,400 litres with a range of 2,500 to 4,250 litres. 6 m^3 of oil was released and 5% would have rapidly evaporated leaving 5,700 litres on the sea surface. Approximately 80% was herded and approximately 4,500 litres were available for burning. About 75% of the herded oil, with a range of 55% to 95%, was estimated to have been burned.

b. **HISB 4.2:** 1,200 litres with a range of 900 to 1,500 litres. 6 m^3 of oil were released and no herding was carried out, leaving a total of approximately 5,700 litres of oil on the sea surface after estimated evaporation. The very fragmented nature of the thick oil in the slick meant that half, or less, of the available oil was ignited, despite 8 ignition attempts.

On the basis that only half of the oil was ignited, it is estimated that approximately 40% (with a range of 30% to 50%) of the oil was burned.

c. **HISB 4.3:** 770 litres with a range of 580 to 960 litres. 4 m^3 of oil were released. After evaporation, approximately 3,800 litres of oil would remain and 96+% of this would have been in the thick oil area. 40% of the thick oil was herded containing approximately 1,500 litres of oil. It is estimated that 50% (with a range of 40% to 65%) of the herded oil was burned.

These results are subject to a high level of probable error. The high average oil layer thickness of 3.2 mm to 4.8 mm in HISB 4.1 just before ignition and the coherent slick contributed to the highest proportion of the herded oil being burned. The fragmented nature of the HISB 4.2 and 4.3 slicks contributed to a lower proportion of the oil in these slicks being burned.

D. Summary of results

Two out of the three experimental slicks (HISB 4.1 and HISB 4.3) were contracted by herder sprayed from the small boat. Herding of the HISB 4.1 slick concentrated about 80% of the thick oil present into a coherent slick that was successfully ignited and the majority of the oil in the slick was estimated to have been burned. Herding of the HISB 4.3 slick resulted in only 40% of the available thick oil being herded. Ignition of the herded portion caused sustained burning, but the fragmented natures of the herded slick caused a lower amount of the oil to be burned. The non-herded HISB 4.2 slick was also successfully ignited. This was because the average oil layer thickness of the thick oil had remained above the minimum required to support burning within the time before ignition.

CONCLUSIONS

The following conclusions were drawn:

1. The experiments demonstrated that oil slicks in calmer open waters can be contracted by herder sprayed from a small boat around the periphery of the thick areas of oil in a slick. The slicks could then be ignited.
2. The greatest difficulty was in observing and locating the areas of thick oil in the slicks from the small boat. This lead to some inaccurate application of the herder and two of the experimental slicks were fragmented into separated thick oil areas by the MOB boats traversing through them before and during ignition.
3. It was estimated that the most oil was burned in the HISB 4.1 slick and 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, but both the herded portion of the HISB 4.3 slick and the non-herded HISB 4.2 slicks were.
4. The higher wind speeds encountered in the HISB 4.3 experiment were one factor in reducing the volume of oil burned, and may indicate an upper limit for HISB in open water condition of 4 to 5 m/s.
5. Residue recovery, despite best intentions, remains challenging given difficulties with tracking the slick over time, as well as other experimental priorities.
6. Further field trials of the concept of large-scale application of herder followed by ignition or use during actual spills will provide better field estimates of likely burn efficiencies achievable with this countermeasure and the weather limitations for its effective use.
7. Testing of full size herder application systems based on a helicopter delivery platform would help minimize and/or eliminate issue related to poor visibility of oil from the water surface. 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.

REFERENCES

BAOAC: Documentation about the BAOAC is publicly available on the Bonn Agreement web site: http://www.bonnagreement.org/

Buist, I., S. Potter and S.E. Sørstrøm. 2010a. Barents Sea field test of herder to thicken oil for in-situ burning in drift ice. Proceedings of the Thirty-third AMOP Technical Seminar on Environmental Contamination and Response, Environment Canada, Ottawa, pp 725-742

Buist, I. A, Potter, S.G., Trudel, B.K., Shelnutt, S.R., Walker, A.H., Scholz, D.K., Brandvik, P.J., Fritt-Rasmussen, J., Allen, A.A., Smith, P. 2014. *In-situ Burning in Ice-Affected Waters: State of knowledge report*. Final report 7.1.1. Final report to the International Association of Oil and Gas Producers (IOGP) Arctic Oil Spill Response Technology Joint Industry Programme (JIP). p. 1-294

SL Ross Environmental Research, 2004, Preliminary research on using oil herding surfactant to thicken oil slicks in broken ice conditions, Report to ExxonMobil Upstream Research, Houston , January 2004

SL Ross Environmental Research, 2005, Small-scale test tank research on using oil herding surfactants to thicken oil slicks in broken ice for in situ burning, Report to ExxonMobil Upstream Research, Houston, TX

SL Ross Environmental Research, 2007, Mid-scale test tank research on using oil herding surfactants to thicken oil slicks in broken ice, Report to MMS, ExxonMobil Upstream Research Company, Agip Kashagan North Caspian Operating Company, Sakhalin Energy Investment Company and Statoil ASA, Herndon VA.

SL Ross Environmental Research, 2012, Research on using oil herding agents for rapid response in situ burning of oil slicks on open water. Report to U.S. Department of the Interior, Bureau of Safety and Environmental Enforcement, Herndon, VA