Basin-scale Testing of ASD Icebreaker Enhanced Chemical Dispersion of Oil Spills

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Abstract

Spring, et al. (2006) describes lab-scale and arctic-basin testing of a concept to utilize azimuthal-stern-drive (ASD) icebreakers to provide the mixing energy required to promote chemical dispersion of oil spilled in a sea ice environment. The combined findings from the lab-scale and arctic-basin tests indicate that an ASD icebreaker is potentially a very effective response tool for oil spills in ice when ambient mixing conditions are insufficient to promote chemical dispersion.

Their testing found that the immense turbulence generated by the prop wash of an ASD icebreaker promotes effective dispersion even after the oil has undergone significant weathering. In addition, the turbulence produces a very fine dispersion that immediately extends up to 20 meters below the sea surface depending on the size of the icebreaker. The depth and quality of the plume limit the resurfacing potential of the oil.

ExxonMobil and BP jointly coordinated and executed four weeks of concept testing in an arctic basin. Spring, et al. (2006) reported on testing completed in 2005. This paper reports on the 2006 arctic basin-testing that evaluated additional spill scenarios. The additional testing found that an ASD icebreaker can enhance chemical dispersion for oil spilled on top of continuous ice, under continuous ice, and within ice leads.

1 Introduction

Concentrated ice on the ocean surface significantly reduces the wave energy available to breakup and disperse chemically-treated oil slicks. Cold arctic temperatures significantly increase the viscosity of certain oils, and viscous, cohesive oils often require considerable mixing energy to induce dispersion.

For oils that are difficult to disperse either because of the characteristics of the oil or the lack of mixing energy caused by the presence of ice, the highly turbulent propeller wash from an azimuthal stern drive (ASD) icebreaker may provide the necessary mixing energy. Figure 1 shows the stern of the FESCO Sakhalin, an ASD icebreaking stand-by vessel, which supports the Exxon Neftegaz Orlan platform offshore Sakhalin Island. In the unfortunate event of a spill, this vessel is available for oil-spill response. Figure 2 shows the surface turbulence that an ASD vessel can create while clearing ice in a channel.

Propulsion of an ASD icebreaker is provided by two pods with propellers, while steering is provided by the capability of the pods to rotate 360°. The pods can be rotated to allow the propellers to face into the direction of travel. The amount of mixing turbulence can be adjusted by rotating the pods to direct prop wash at the surface oil slick. These vessels utilize the double-acting concept that allows them to be effectively utilized in both ice and open-water conditions. When penetrating thick ice or ice rubble, the vessel usually moves stern first. The stern-first operation in ice means that the propellers are easily positioned adjacent to an oil slick without interference from the hull to directly apply the prop wash at the slick.

The pods of a vessel such as the FESCO Sakhalin are approximately 5 m below the water line, and the propeller wash extends 15 to 20 m below the water surface. Thus, a dispersed oil plume generated by this propeller wash can immediately extend over 15 m below the water surface.

This reduces the likelihood of oil resurfacing because (1) dispersed oil droplets are rapidly diluted thereby reducing particle collision and coagulation and (2) relative to wave induced dispersion where the maximum initial particle entrainment depth is on the order of 1 m, the average dispersed oil droplet caught in ASD prop wash must rise from a far greater water depth.

In addition, a coarse oil droplet entrained in propeller wash experiences a long period of shearing conditions that can break it into smaller droplets because it remains in highly turbulent conditions throughout the 15 to 20 m deep plume. For breaking waves, the highly turbulent conditions are limited to the near surface.

The flexibility of the rotating pods, the stern-first operation, and the depth of the turbulent plume makes this type of vessel ideal for supporting a chemical-dispersion operation. Although there are a limited number of ASD icebreakers in operation today, they are expected to replace standard icebreakers in the future because of their double-acting capabilities and superior performance.

Figure 1 Stern of FESCO Sakhalin.

Figure 2 Open water created by the Finnish ASD Icebreaker Fennica.

Spring, et al. (2006) reported on a three phase study to evaluate the potential of utilizing ASD icebreakers to enhance chemical dispersion. The study culminated with tests that used a 1:25 scale model of the FESCO Sakhalin icebreaker and the Aker Arctic ice basin located in Helsinki, Finland. These tests were completed in December 2005. In January 2006, testing using the same model and ice basin was conducted to evaluate additional spill scenarios.

2 Background

2.1 Previous Testing

The SL Ross indoor wave tank (10 meters long by 1.2 meters wide by 1.2 meters deep) was used to conduct preliminary testing of the concept using a trolling motor to simulate an ASD pod. Figure 3 shows the experimental set-up used for these tests. Sakhalin Island Chayvo crude oil collected from the Z6 well was used in all tests and the dispersant used was Corexit 9527. Some spill-related properties of this oil are shown in Table 1. Details of the test method are provided in Spring, et al. (2006).

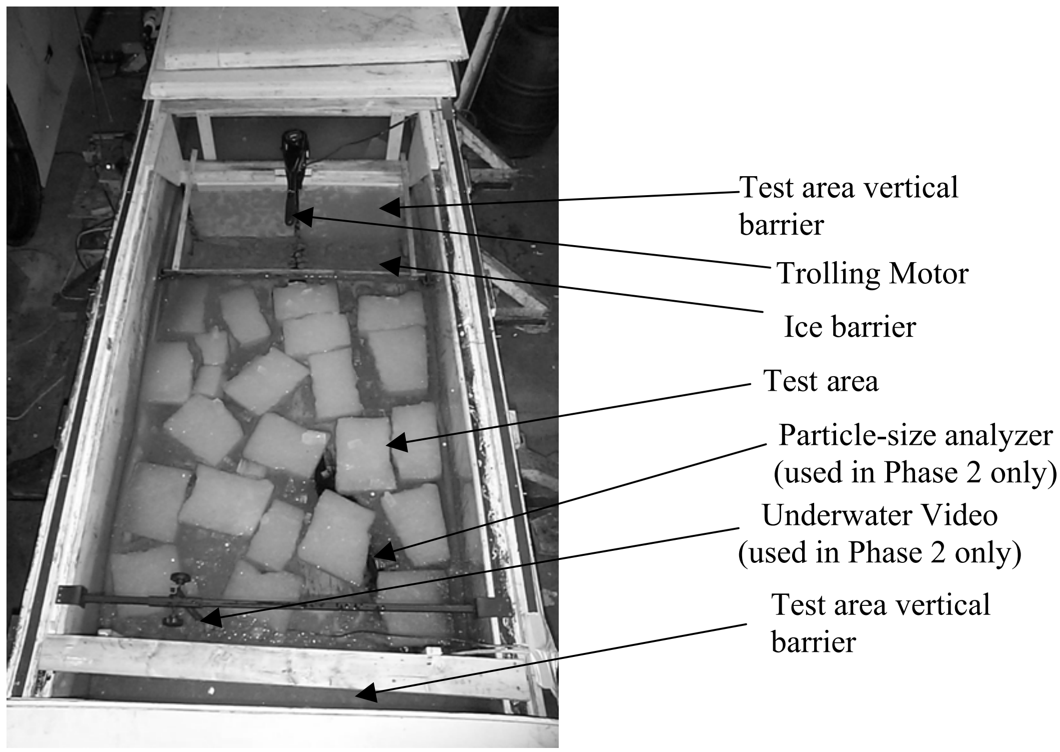

Figure 3 Test set-up at the S.L. Ross facility.

The lab-scale tests found that the use of propeller wash resulted in >90% dispersion for most tests in ice concentrations ranging from 25% to 95%. Other important findings from this study were (a) lower dispersant to oil ratio (as low as 1:110) resulted in high dispersion and (b) Chayvo crude oil weathered for 98 hours (>4 days) was still dispersible compared to baffled flask tests which had indicated dispersant effectiveness was reduced between 48 and 72 hours at 0°C.

The successful lab-scale tests led to tests using a larger test basin (the Aker Arctic Technology (AAT) basin in Helsinki, Finland). The initial basin tests utilized a 1:25 scale model of the FESCO Sakhalin icebreaker, Chayvo Z6 crude oil, and Corexit 9527. Details of the test method are provided in Spring, et al. (2006). These arctic basin tests confirmed the lab-scale tests results with tests typically resulting in >90% dispersion.

The magnitude of the dispersed oil plume generated by the prop wash of the FESCO Sakhalin was observed during these initial tests (see Figure 4). Considering the

1:25 scale of the tests, the model of the FESCO Sakhalin icebreaker produced a plume that immediately extended roughly 20 m below the water surface.

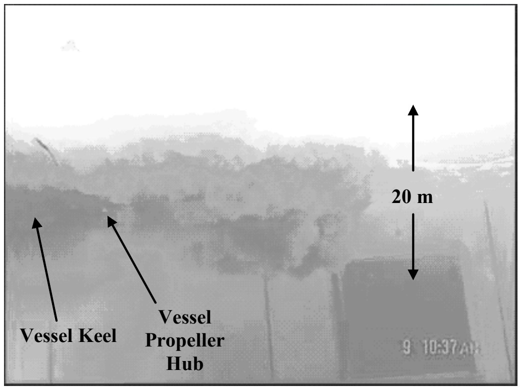

Figure 4 Dispersed oil plume generated by the 1:25 scale model in the AAT basin. The plume penetrates roughly 20 m below the surface.

Table 1 Spill-related Properties of Chayvo Z-6 Crude Oil

Parameter	Z-6	Z-6	Z-6	Method
Evaporation carried out at 20°C (volume %)	0	28.57	39.73	Wind tunnel at 10 knots
Density (g/cm^3)				ASTM D4052-91
0°C	0.848	0.878	0.890	
5°C	0.844	0.874	0.885	
Dynamic Viscosity (mPa·s) shear (s^{-1})	400	100	30	ASTM D2983-87
0°C	16.8	355.8	6208	
5°C	12.0	176.2	3982	
Kinematic Viscosity (mm^2/s)				
0°C	19.8	405.0	6979	
5°C	14.2	201.5	4500	
Interfacial Tension (dyne/cm)				ASTM D971-82
Oil/Air	28.4	30.6	31.0	
Oil/Seawater	20.7	23.3	28.1	
Pour Point (°C)	0	15	21	ASTM D97-87
Flash Point (°C)	<-5	73	111	ASTM D93-90
Emulsion Formation-Tendency and Stability	@ 0°C			Mackay and Zagorski, 1982; Fingas et al., 1998
Tendency Index	very unlikely	very likely	very likely	
Stability Index	Unstable	entrained water	entrained water*	
Water Content (after 24 hr)	17%	29%	76%	
Emulsion Formation-Tendency and Stability	@ 5°C			
Tendency Index	very likely	very likely	very likely	
Stability Index	entrained water	entrained water	entrained water*	
Water Content (after 24 hr)	26%	52%	88%	

*Entrained water emulsions have a water content of between 26 and 62%. These emulsions were characterized as entrained water because of observations of large water droplets; however, the large water droplets were likely mechanically stabilized by gelling of the high pour point samples.

3 Final Arctic Basin Testing

BP and ExxonMobil jointly funded, coordinated, and executed additional arctic basin testing of the ASD icebreaker concept. The tests used the same crude oil (Chayvo Z6), dispersant (Corexit 9527), AAT arctic basin, and ASD icebreaker model (Figure 5 and Figure 6) as in the initial tests. The final series of tests expanded the number of spill scenarios evaluated from the five scenarios previously reported to a total of eleven. The eleven scenarios include those expected to simulate many of the most probable ice conditions in the unlikely event of a spill in dynamic ice such as occurs offshore Sakhalin Island in Russia.

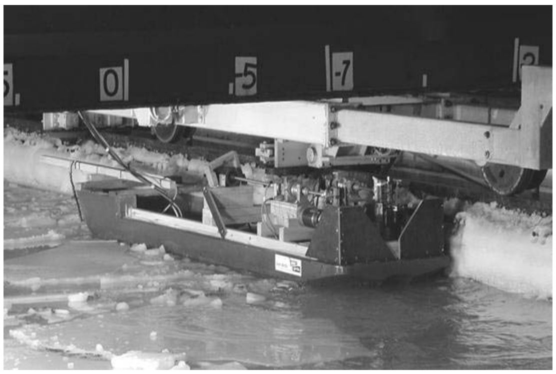

Figure 5 FESCO Sakhalin model viewed toward stern.

Figure 6 Model working in level ice.

The eleven tests evaluated oil spilled in the following ways:

- within ice leads at air temperatures of -3°C to -4°C and at a slightly colder temperature of -10°C
- on top of ice with and without snow cover
- under ice
- on ice rubble and in leads between ice rubble
- in low ice concentrations

Corexit 9527 has been used throughout the evaluation of the icebreaker-enhanced dispersion concept. BP and ExxonMobil conducted this research to enhance oil-spill response activities at Sakhalin Island in Russia. Corexit 9527 is the only widely available dispersant approved for use in Russia. The positive results of the testing with Corexit 9527 strongly suggest that other commercially available dispersants would be effective.

3.1 Test Set-up and Procedures

The January 2006 tests were completed using the AAT ice test basin that was demolished later in 2006 when AAT moved to new facilities. The AAT ice basin was 77.3 m in length, 6.5 m in width and 2.3 m deep and filled with 32 ppt salt water. The test tank was contained within a cold room used to lower the air temperature when making ice. Nortala-Hoikkanen (1990) describes the process of making ice in the AAT facility and also the ice strength properties obtained. Ice strength properties were not measured in this series of tests as they were expected to have limited effect upon the vessel mixing concept being tested.

Figure 5 shows the 1:25 scale model of the FESCO Sakhalin used in the tests. A "bowsprit" was used to mount and hold a droplet particle size analyzer (LISST - 100 manufactured by Sequoia Scientific, Inc.) sensor 0.5 m below the water surface. As this icebreaker primarily operates stern first when breaking ice, the LISST was placed at the bow to be downstream of the propeller wash in order to collect oil droplet size data throughout each test.

For tests with oil on ice or in ice leads, the test area was prepared with the desired ice floe size and concentration, oil was poured either on the ice surface or in leads, dispersant applied using an industrial pump-up sprayer, and the vessel was moved through the oil to provide the mixing energy. Figure 6 shows the vessel during a test where oil was spilled upon a level ice sheet.

To quantify the amount of oil dispersed during a test, the oil remaining after a test was sorbed from the tank surface using absorbent pads; the absorbents were dried overnight and weighed the next day to determine the amount of undispersed oil. Approximately 30 minutes of time elapsed between the end of the vessel mixing process and the start of residual oil clean up.

Only one type of control test was performed during testing in the AAT basin. The control run was made during the initial December 2005 testing to evaluate the ability of the vessel to disperse a slick of Chayvo crude oil without using dispersants. The AAT basin does not have wave-generating capabilities that would have allowed comparison to open water control tests as was done for the previous lab-scale tests.

For this control run, the amount of dispersion was very limited—qualitatively estimated at <20%. The large volume of oil used in this test and difficulties encountered skimming the undispersed oil from the surface after the test did not allow quantitative measurements. There was too much residual oil to use the sorbent-pad cleanup method. The limited dispersion was confirmed by the clarity of the water after the control tests (first test in the basin) and the immediate resurfacing of oil entrained in the prop wash as observed through underwater viewing ports.

The challenge of cleaning up the residual oil used in the first two tests in the AAT basin (the control test and the low (1:110) dispersant to oil ratio test) resulted in reducing the amount of oil used for each test from 37.9 liters to 18.9 liters. This reduction was not expected to bias the test; in fact, the smaller resulting slicks were less likely to contact the basin walls during the testing.

Only a single control run was completed for arctic-basin testing for two reasons. First, as just mentioned the only control possible was to run the icebreaker without dispersants and without waves. This would not be a recommended field practice as the lab-scale testing indicated that chemical dispersants combined with the vessel mixing were needed to generate an effective dispersion. The second reason was that additional control tests unrepresentative of expected field conditions could not be justified because of the expense associated with each test. The ideal control would use chemical dispersants combined with wave-induced mixing and no vessel mixing.

It was clear during the testing that because of the large size of the tank the cleanup method somewhat decreased the accuracy of the measurement to quantify the amount oil dispersed. It was decided to concede test accuracy to maximize the number of tests performed in the limited amount of tank time available. Based on observations, however, it is unlikely that the amount of oil on the surface of the test tank after cleaning with absorbents was more than the amount collected by the absorbents and in most cases it was likely much less. Considering that most tests resulted in more than 90% dispersion, a more accurate test procedure may have lowered the amount of dispersion between 5 and 10% at most.

In all tests, some dispersed oil remained on the ice surface as a brownish stain. Very little oil was observed adhering to the basin walls, and this oil was easily recovered with the absorbent pads.

To evaluate the magnitude of oil lost to staining, a piece of ice with one of the darkest stains was collected and melted in a container. The melted water surface in the container had approximately the same area as the stained ice surface. After melting the stained ice, the oil that was released formed a sheen that was <0.1 mm thick.

Observations made during basin tests were that the stained surface, whether from untreated oil or dispersed oil, covered an area that was at most the area of the original spill, but most of the time the area of staining was significantly less than the original spill area. Estimates of the oil thickness for the 75% ice cover tests ranged from 6 mm to over 20 mm. At a thickness of 6 mm, a 0.1 mm residual stain covering the same surface area as the original spill accounts for <2% of the starting oil volume. Thus, the un-recovered oil adhering to ice had a minimal effect on the accuracy of these tests.

3.2 Results

The matrix and results for the initial tests are shown in Table 2 and for the final tests in

Table 3. Sixteen different tests were completed with eight being completed in the final (2006) tests. Most tests used 1:20 DOR, but two tests were completed at 1:110 DOR.

A detailed discussion of the results for the initial tests is provided by Spring et al. (2006). To summarize, the initial tests resulted in effective dispersion for spills in leads, on top of ice, and in leads at colder air temperatures.

The final test series evaluated the very challenging conditions of spills under ice as might occur after a spill from a subsea pipeline, spills both on ice rubble and in ice rubble leads, and spills in low-concentration of ice.

One test in the final test series was a repeat of the low dispersant-to-oil ratio (1:110 DOR) test completed earlier. The initial low DOR test was completed while the test protocol was being developed and quantitative results were not obtained. The second low DOR test (Test 7-1) resulted in good dispersion (84%). The particle size data collected for test 7-1 was somewhat higher than other successful tests. The average mean and median droplet diameter for all sampling events during the 7-1 test were 144 µm and 125 µm, respectively compared to mean/median diameters generally well below 100 µm for the other tests.

For spills of oil under ice (Tests 5-1 and 7-2), the test procedure was modified somewhat. After placing the oil under the ice by pumping through a hole in the surface, the icebreaker first released the oil by breaking the ice. The vessel broke the ice operating stern first for test 5-1 and bow first for test 7-2. These different icebreaking methods were used to determine if the bow first method would limit displacement of the oil slick further under unbroken ice, which was observed with the stern-first icebreaking, and improve the process. After releasing oil to the surface, dispersant was applied to the oil using the pump-up sprayer. Then the icebreaker made a second pass through the oil to disperse it. The dispersion rate dropped to 70-80% for these tests because the vessel was not able to encounter all of the oil during the initial breaking process. During the second pass, the vessel encountered several pockets of oil under the ice that had not received dispersant. The bow-first icebreaking method provided some improvement (78% versus 72% dispersion).

Table 2. Phase 3 December 2005 Test Matrix and Results (Spring, et al. 2006)

	Control and low DOR		**Oil among ice floes**		**Oil on ice**		**Oil among ice floes (cold air)**	
Scenario Tested	**Test 1-1**	**Test 1-2**	**Test 2-1**	**Test 2-2**	**Test 3-1**	**Test 3-2**	**Test 4-1**	**Test 4-2**
Ice thickness (m)	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Floe Size (m)	60	60	60	30	NA	NA	60	NA
Ice Concentration	75	75	75	75	100	100	75	100
DOR	0	1/110	1/20	1/20	1/20	1/20	1/20	1/20
Oil Amount (liters)	37.9	37.9	18.9	18.9	18.9	18.9	18.9	18.9
Air Temperature	-4.7°C	-4.1°C	-3.6°C	-3.0°C	-4.0°C	-3.0°C	10.8°C	10.3°C
Weathering	3%	3%	3%	3%	4.3%	4.3%	4.3%	4.3%
Dispersed oil D_{mean}/D_{50} (μm)	215/189	157/121	48/26	43/20	46/23	65/29	68/37	96/50
Amount oil dispersed (%)	<20%	No data	94.2	93.7	96.3	98.2	94.1	96.9

Table 3. Phase 3 January 2006 Test Matrix and Results

	Oil Under Ice IB Stern First	**Oil on snow covere d ice**	**Oil on ice rubble**	**Oil in low ice conc.**	**Low DOR**	**Oil under ice IB Bow First**	**Oil in low ice conc.**	**Oil in ice rubble leads**
Scenario Tested	**Test 5-1**	**Test 5-2**	**Test 6-1**	**Test 6-2**	**Test 7-1**	**Test 7-2**	**Test 8-1**	**Test 8-2**
Ice thickness (m)	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Floe Size (m)	NA	NA	NA	30	NA	NA	60	30-60
Ice Concentration	100	100	100	25	100	100	50	75
DOR	1/20	1/20	1/20	1/20	1/110	1/20	1/20	1/20
Oil Amount (liters)	18.9	18.9	18.9	18.9	18.9	18.9	18.9	18.9
Air Temperature	-2.6°C	-0.4°C	-4.5°C	-3.8°C	-3.7°C	-3.5°C	-1.7°C	-5.2°C
Weathering	6.2%	6.2%	6.2%	6.2%	6.2%	6.2%	6.2%	6.2%
Dispersed oil D_{mean}/D_{50} (μm)	No data[*]	No data[*]	62/38	67/40	144/125	No data[**]	67/46	117/89
Amount oil dispersed (%)	71.5	96.5	92.8	68.1	84.0	78.4	87.0	95.7

[*]Particle-size analyzer malfunctioned
[**]Particle-size analyzer removed from bow of vessel due to bow-first icebreaking.

The oil under ice tests had two basin-effect issues that may not be encountered in a real spill. First, the vessel operator was able to see the large oil mass through the ice sheet allowing a direct attack and high encounter rates. In a real spill, the vessel operator would have limited information on the exact location of the spill under the ice. This would hinder cleanup of a real spill. Second, the ice sheet grown for these tests was relatively smooth on both surfaces. This caused the vessel to easily push oil further under the ice during the first ice-breaking step thereby reducing the amount that was released to the surface. Natural ice has very rough surfaces, and the roughness will form natural boundaries restricting the movement of oil under ice. The natural roughness and boundaries of field ice will likely help cleanup efforts when oil is encountered.

Effective dispersion was achieved for tests when oil was spilled on top of ice rubble and in ice rubble leads (Tests 6-1 and 8-2). For these two spill scenarios, ice rubble had a positive effect as the rough surface of the rubble helped to keep treated oil from spreading away from the propeller thrust.

The tests with lower ice concentrations (tests 6-2 and 8-1) indicate that higher ice concentration positively influences dispersion. As the ice concentration decreased, the amount of oil dispersion decreased. For the 25% ice concentration test (test 6-2), 68% dispersion was measured. The higher ice concentrations provided a barrier that contained the oil allowing the vessel thrust to be directed at it. As the ice coverage decreased, this containment is lessened and the vessel had to chase after smaller and smaller oil slicks.

The proximity of the basin walls did have a positive influence upon the dispersion rates obtained in that they acted to contain the spill in one area. This effect, however, was likely only significant during the low ice concentration tests and not significant in the high ice concentration tests. In an actual spill, larger ice floes will act in a manner similar to a basin wall and help contain spilled oil in the leads and openings of the ice field.

To evaluate the thousands of samples analyzed by the LISST particle-size analyzer during the basin tests, both the median and mean particle size (based on total particle volume) determined for each sampling event were averaged for a test. The average median particle diameter for all tests ranged from 20 μm to 89 μm for all tests that used a 1:20 DOR. The average mean particle diameter for all 1:20 DOR tests ranged from 43 μm to 117 μm .

With an oil droplet density of 0.85 g/ml and a seawater density of 1.025 g/ml, Stokes Law estimates that the rise velocities of dispersed oil would be 0.017 and 0.134 cm/s for 43 μm and 117 μm droplet diameters, respectively. These particles would require between 2 and 16 hours to rise 10 m in quiescent water.

4 Discussion and Conclusions

The results of the 2006 arctic-basin testing further demonstrates that ASD icebreakers could be an important tool able to enhance chemical dispersion and should be considered for spills in ice where dispersants are an accepted response option. The additional testing provides evidence that an ASD icebreaker can promote chemical dispersion of spilled oil for important spill scenarios of oil under ice and oil in ice rubble leads.

Other important findings from the complete study were as follows:

- Dispersant to oil ratio as low as 1:110 resulted in effective dispersion.

- Chayvo crude oil remained dispersible using ASD prop wash for at least twice as long as with wave energy alone (at least 4 days compared to 2 – 3 days).
- The plume entrainment depth (up to 20 m) resulting from the vessel mixing process will significantly lower the chance of resurfacing of dispersed oil.
- The mean dispersed oil droplet size measured during the basin tests was on the order of requires multiple hours to rise 3 m in quiescent water. Given that the dispersed plume produced by the icebreaker is expected to be roughly an order of magnitude deeper than a wave dispersed plume, these small droplets are also unlikely to resurface even in very low energy conditions.

5 References

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