POTENTIAL EFFECTIVENESS OF DISPERSANT USE IN THE U.S. BEAUFORT AND CHUKCHI SEAS

for:

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Executive Summary

The objective of the study has been to provide information to support dispersant use decision-making with respect to oil spill chemical dispersant effectiveness under the environmental conditions likely to be encountered in the U.S. Beaufort and Chukchi Seas.

The goals of the goals research were to:

1. Identify the prevailing environmental conditions in the U.S. Beaufort and Chukchi Seas that would affect dispersant performance (see Section 4 of this report);
2. Identify existing dispersant effectiveness tests that have been completed on Alaskan oils under conditions similar to those that exist in these two regions and identify gaps in the knowledge of dispersant effectiveness (see Section 5 of this report);
3. Conduct dispersant effectiveness tests at medium scale to address the knowledge gaps (see Section 7 of this report);

The primary environmental factors that have been shown to influence dispersant effectiveness include: wave energy; water salinity; water temperature; and presence and concentration of ice.

With the exception of isolated near shore fresh water outlets there is minimal variation (between 28 to 34 ppt (parts per thousand)), both temporally and spatially, in surface water salinity throughout the U.S. Chukchi and Beaufort Sea regions, at least from a chemical dispersant effectiveness standpoint. The performance of most chemical dispersants is generally not affected by salinity in the range of 25 to 35 ppt. Water salinities in the nearshore area of the Beaufort and Chukchi Seas can be considerably lower than the offshore areas for short periods of the year due to the influence of fresh water river outflows and ice melt. Fresh water from river outflow can form a 1 to 2 m deep lens under the landfast ice that may extend up to 25 km offshore from the major river mouths. The surface water salinities in these areas approach that of fresh water during the early ice breakup period and prior to the mixing of the upper and lower water layers by strong winds and waves. The presence of this near shore fresh water during this period could hinder the effectiveness of chemical dispersants.

The surface water temperatures in the Chukchi and Beaufort Seas in the open water seasons can vary from close to freezing (-2 °C) to upwards of 10 °C. The chemical dispersibility of crude oil is affected by the temperature only as it affects the viscosity of the oil. The oil's viscosity is affected by the water temperature on which it sits and during sunny days by the heating of the surface of the oil by the sun. Different crude oils can have very different viscosities at the same temperature and many can be quite fluid at temperatures near freezing. There is really no water temperature that will completely restrict the use of chemical dispersant. The oil viscosity – temperature relationship must be considered for each oil before an evaluation of the potential for dispersant effectiveness can be made.

The presence of greater than 9/10ths ice cover eliminates the possibility of using conventional surface applied dispersant operations. The presence of the ice either encapsulates the oil making it impossible to target with aerial applied dispersant or dampens the surface energy such that there is insufficient energy to break the oil into droplets once treated. In ice conditions with less than 3/10ths cover chemical dispersants will perform much the same as in open water conditions since the surface mixing energy is not overly dampened by the presence of the ice. The performance of dispersants in 3/10ths to 8/10ths ice cover without additional mixing energy applied is somewhat uncertain. Research suggests that performance may be enhanced in these conditions by the energy generated at the ice edge as the ice pieces jostle even under low wave energy. In the Chukchi Sea region open water periods can exist in the months from June through November depending on the year. Open water is most common in the months of July through October in this region but the shoulder months of June and November may present dispersant application opportunities depending on the ice year. In the Beaufort Sea region the maximum likely extent for open water dispersant use is from July to October with the more likely season being from August to October.

Long term historical wave height data is not available in the U.S. Chukchi and Beaufort Sea regions for statistical assessment of the potential for successful dispersant use on a broad geographic scale. Long term wind data are, however, available for the region in the form of offshore hindcast wind data sets. Wave heights based on the Beaufort wind scale have been derived from hindcast wind speed data for this project. The percentage of time that wave heights favorable for chemical dispersant use exist in the US Beaufort and Chukchi Seas has been determined based on an assessment of 30 years of hindcast wind data from 5 stations located across the study area. For the open water months of July through October wave conditions favourable for chemical dispersant use exist across both regions from 71 to 91% of the time. These assessments do not take into account other variables such as visibility or daylight.

A review of scientific literature on the results of chemical dispersant effectiveness tests specifically conducted on Alaskan crude oils has been undertaken. Research that investigated chemical dispersant effectiveness under arctic conditions and in the presence of ice using other oil types has also been included in the review due to paucity of research in this area. The review has focused on the parameters that could affect dispersant performance that are of specific concern to the arctic environment. These parameters include the test temperature, the water salinity, the mixing energy and the presence of ice. Oil type, dispersant type and dispersant dosage have also been considered in this review. With a few exceptions, only tests that have used Alaskan oil have been reviewed. Only 10 of the 48 test programs reviewed studied dispersion in the presence of ice and only 7 of these varied the ice concentration in the test matrix and only two used Alaskan oil in the testing. Of the 48 studies reviewed, temperature was varied in 15, salinity was varied in 16, and mixing energy was varied in 29.

At the present time the only oils being produced and transported (by pipeline to shore) in the Beaufort and Chukchi Seas are Northstar and Endicott crude oils and are the only crude oils that could be spilled directly into Alaskan offshore waters from present production fields. No oils are presently being produced in Chukchi Sea waters. Alaska North Slope Crude (ANS), or Prudhoe Bay crude as it was named in early test programs, has been the Alaskan oil of choice for most of the dispersant effectiveness tests conducted on Alaskan oils. This oil is the pipeline blend that is transported to Valdez via the Trans-Alaska Pipeline. Only five of the test programs reviewed evaluated dispersant effectiveness on specific North Slope production crudes (Endicott, Northstar and Pt. McIntyre). These oils were used in projects that were conducted for the US Department of the Interior with oils sourced by them specifically for cold water dispersant effectiveness testing. These oils are possibly more representative of the type of crude that might be spilled in the Beaufort and Chukchi Seas. As new oils come into production in the waters of the Beaufort and Chukchi Seas they should be evaluated for their potential for chemical dispersion under the range of environmental conditions they might be spilled in.

Most of the past dispersant effectiveness tests on Alaskan oils used one or both of Corexit 9500 and Corexit 9527 in their testing.

There is concern in temperate or subarctic climates that temperature is a problem in dispersant effectiveness and that dispersants should not or cannot be used in cold climates. This concern is generally unfounded based on the research results, except in the case of so-called "high pour point oils", some of which can become semi-solid at temperatures well above freezing. Reduced temperature simply increases the viscosity of the spilled oil. The viscosity of the oil at the water temperature in which it is spilled is the key factor in deciding dispersant effectiveness and not the temperature per se. This points to the need to fully understand the properties of the specific oils that are likely to spilled in cold waters.

Numerous laboratory-scale, meso-scale and field studies, dating back to the late seventies, have been conducted to study the effect of water salinity on the effectiveness of oil spill chemical dispersants on a range of oils. The consistent significant finding of all of these tests is that dispersant designed for use in marine environments (30 to 35 ppt water salinity) are considerably less effective when the water salinity falls below about 20 ppt or above 40 ppt. Of the dispersants most commonly used in US waters, Corexit 9500 has been shown to be more effective than Corexit 9527 in lower salinity waters. Dispersants have been formulated for use in fresh water and these have also been tested for effectiveness over a range of water salinities, although not as extensively as the marine dispersants. The effectiveness of the freshwater dispersants have been shown to generally be much better than the marine products in freshwater but often achieve their best results in waters between 10 and 20 ppt salinity. The effectiveness of dispersants on the Alaskan oil under varying water salinities generally is consistent with the findings for other crude oils in these historical studies.

Tests conducted in the past few years using the more energetic US EPA baffled flask test have indicated that the effect of salinity on dispersant effectiveness may not be as significant as identified in the earlier work. This may be due to the higher mixing energy imparted in this test.

After considering the above factors and discussion with a technical representative from the Bureau of Safety and Environmental Enforcement (BSEE), a suite of dispersant effectiveness tests using the SL Ross meso-scale wind-wave tank on four Alaskan crude oils with four water salinities were selected for additional study to shed more light on the effectiveness of marine dispersants over a range of water salinities under high energy breaking wave conditions.

Alaska North Slope, Endicott, Northstar and Kuparuk crude oil were used in the testing. Tests were conducted on fresh, evaporated and evaporated plus emulsified crude oils (3 weathered states in total). Northstar does not form a stable emulsion so tests could not be conducted on emulsions of this oil. Tests were conducted in water with salinities of 5, 10, 20 and 30 ppt. All tests were conducted with a water temperature of 10 °C. Corexit 9500 was applied at a dispersant to oil ratio of 1:20 in all tests.

The oil collected from the surface containment zone at the end of each test was compared to the volume of oil initially released to determine the quantity of oil removed from the surface during the test or the raw dispersant effectiveness (DE_{raw}).The DE_{raw} estimates have been adjusted by multiplying them by the volume fraction of oil present in drops smaller than 70 microns to arrive at a final dispersant effectiveness estimate that is referred to as DE_{70} throughout the report. The 70 micron drop size value has been reported as being the maximum oil drop size that will remain dispersed based on a series of field tests.

The fresh oils were more effectively dispersed than the weathered oils that were more effectively dispersed than the weathered and emulsified oils. The most complete data sets collected (due to limitations of the LISST in measuring large oil drops) were for the fresh oil tests. The results for the fresh oils indicate that the DE_{70} values are highest for the 30 ppt water and in all cases drop linearly as the test water salinity decreased to 5 ppt. The Northstar crude was most easily dispersed with complete dispersion (> 95% DE_{70} in 20 ppt salt water), followed by fresh ANS

(95% DE_{70} in 30 ppt salt water), fresh Kuparuk (85% DE_{70} in 30 ppt salt water) and Endicott (40% DE_{70} in 30 ppt salt water). The DE_{70} dropped linearly to a value between 15 to 25 % for the oils tested as the water salinity decreased to 5 ppt. Similar linear trends in DE_{70} reduction with decreasing water salinity were identified in the weathered oil tests.

The highest DE_{70} recorded for any of the emulsified oils was 20% in 30 ppt salt water.

Even under the high energy breaking wave conditions used in this test program it would appear that water salinity had a significant effect on the ability of Corexit 9500 dispersant to assist in the generation of small oil drops that would likely remain dispersed in an ocean setting. The effect noted was the linear decrease in the volume of oil drops generated with small enough size to remain dispersed as the water salinity decreased from 30 ppt to 5 ppt.

The oil drops in some of the tests were visibly larger than the upper measurement limit of the LISST device used to measure oil drop size distributions and reliable drop size data could not be gathered for these tests. Development of an in-situ oil drop measurement system capable of cost-effectively measuring drop sizes in the 10 to 3000 micron range would improve the state-of-the art in oil dispersion monitoring both in large tank and field test conditions.

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Chemical Dispersant Research: Dispersant Effectiveness Testing at Ohmsett Using Aircraft Application Dosages

1 Objectives

The objective of the study has been to provide information to support dispersant use decision-making with respect to dispersant effectiveness under the environmental conditions likely to be encountered in the U.S. Beaufort and Chukchi Seas.

2 Goals

The goals of the proposed research were to:

4. Identify the prevailing environmental conditions in the U.S. Beaufort and Chukchi Seas that would affect dispersant performance (see Section 4 of this report);
5. Identify existing dispersant effectiveness tests that have been completed on Alaskan oils under conditions similar to those that exist in these two regions and identify gaps in the knowledge of dispersant effectiveness (see Section 5 of this report);
6. Conduct dispersant effectiveness tests at medium scale to address the knowledge gaps (see Section 6 of this report);
7. Write a technical report on the study and a technical paper for presentation at a suitable oil spill conference or technical seminar (delivered under separate cover).

3 Background

In the event of an offshore oil spill rapid decisions must be made with regard to the best course of action to mitigate potential effects of the spillage. Chemical dispersants are one of the tools to be considered. The initial question to be answered when deciding if dispersant application is an appropriate action is “Will the dispersant be effective in removing a significant percentage of the oil from the surface?” If not, then the dispersant operation would not be considered. If chemical dispersants are deemed to be potentially effective other issues such as a) the logistical feasibility of getting the dispersant to the spill site; b) applying it at the appropriate dosage; and c) the net environmental benefit of using the dispersant must also be considered in the decision making process prior to the final approval for dispersant use. This report addresses only the issue of dispersant effectiveness.

The potential effectiveness of a chemical dispersant will depend on the type of dispersant used, the type and weathered state of the oil to be treated, and the prevailing environmental conditions at the time of application (water temperature, water salinity, wave energy present and presence of ice). A number of dispersant effectiveness studies have been completed using Alaskan oils, in warm and cold waters, in different water salinities, and in the presence of ice, including several studies funded by the US Department of the Interior. This report provides a focused review of this research, a review of the range of environmental conditions that could be encountered in the two regions during a dispersant application operation and the identification of additional research requirements regarding the use of dispersants specific to the U.S. Beaufort and Chukchi Sea regions. Meso-scale tank tests of dispersant effectiveness on four Alaskan crude oils have also been conducted in this study to help fill in some of the knowledge gaps on dispersant use under conditions that could be encountered in these regions.

4 Typical Environmental Conditions in the U.S. Beaufort and Chukchi Seas that Affect Dispersant Effectiveness

The primary environmental factors that have been shown to influence dispersant effectiveness include: wave energy present at the time of dispersant application or shortly after the application; water salinity; water temperature (primarily the effect of temperature on the oil's properties of viscosity and pour point); and presence and concentration of ice (and the influence of the ice on the surface and sub-surface mixing energy). The range of conditions that exist for these four parameters in the U.S. Beaufort and Chukchi Sea regions are documented along with their variability on both a seasonal and spatial basis on a scale appropriate for decision purposes.

4.1 Water Salinity

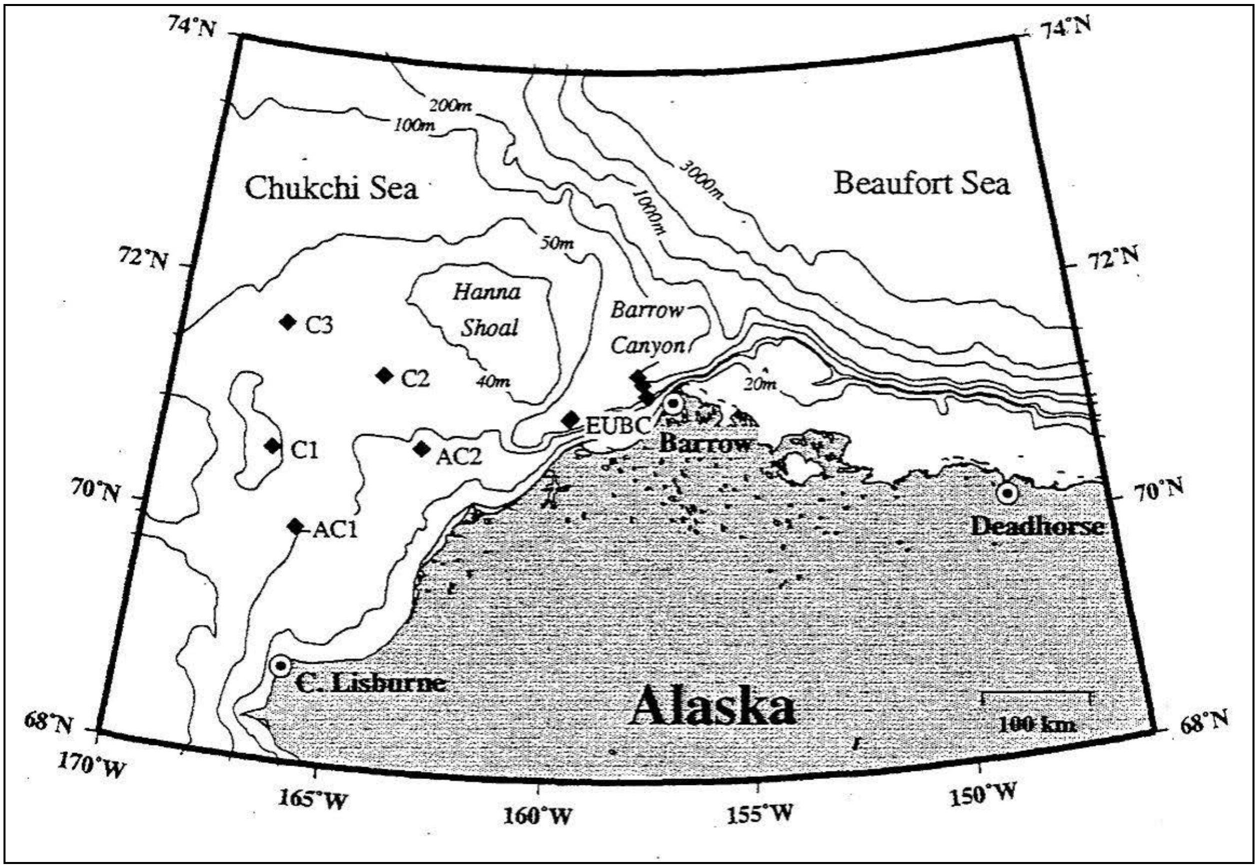
With the exception of isolated near shore fresh water outlets there is minimal variation, both temporally and spatially, in surface water salinity throughout the U.S. Chukchi and Beaufort Sea regions, at least from a chemical dispersant effectiveness standpoint. The performance of most chemical dispersants is generally not affected by salinity in the range of 25 to 35 ppt (SL Ross

2010). Studies at specific offshore sites have identified surface water salinity variation between 28 and 34 ppt (Weingartner and Danielson 2010, Weingartner et al. 2005). Weingartner (1998) also measured surface water salinity at various locations in the Chukchi Basin (see Figure 4-1). Seasonal surface water salinities were shown to vary between about 30 to 34 ppt (Figure 4-2), well within the range for effective chemical dispersant use. Figure 4-3 shows salinity measurements, also made by Weingartner, along an east-west transect from Barrow AK to Wrangel Island in the west. Measured salinities in all of these cases ranged from about 29 to 32 ppt.

Measured surface water salinity in the Beaufort Sea offshore region ranges between 27 and 34 ppt (Aagaard et al,1988, Proshutinsky et al, 2003, Weingartner et al. 2006). Figure 4-7 and Figure 4-8 show salinity profiles measured by Aagaard for the western and eastern extents of the Beaufort Sea (transects W and D shown in Figure 4-6). The salinities are somewhat lower 28 to 29 ppt in the east versus 28 to 31 in the west. Weingartner's salinity measurements were made at the sites along the outer shelf identified in Figure 4-4. Figure 4-5 shows the measured surface water salinities that were taken along the shelf. The salinities vary from about 32 ppt in the west to about 29 in the east. The salinities in all reported cases for the offshore Beaufort Sea region are sufficiently high that chemical dispersant effectiveness would not be significantly affected. Proshutinsky also concluded that "In ice-free regions, seasonal temperature fluctuations reach up to several degrees, whereas salinity fluctuations are small."

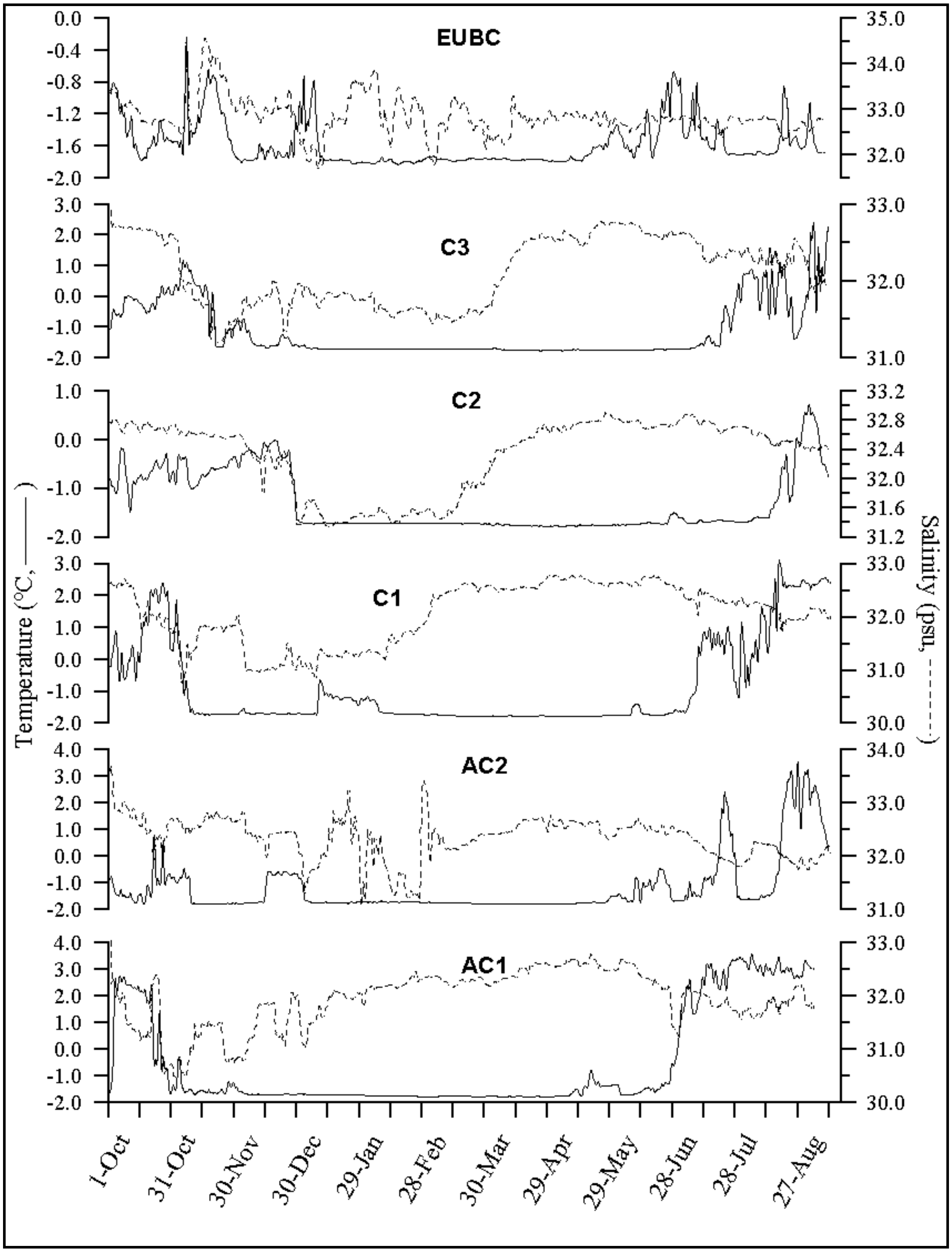
Water salinities in the nearshore area of the Beaufort Sea can be considerably lower than the offshore areas for short periods of the year due to the influence of fresh water river outflows and ice melt. Fresh water from river outflow can form a 1 to 2 m deep lens under the landfast ice that may extend up to 25 km offshore from the major river mouths (Weingartner et al. 2005). The surface water salinities in these areas approach that of fresh water during the early ice breakup period and prior to the mixing of the upper and lower water layers by strong winds and waves. The presence of this near shore fresh water during this period could hinder the effectiveness of chemical dispersants. However, dispersants are generally not approved for use in waters less than 10 m, so this may not be an issue depending on the extent of the surface freshwater plume offshore.

Nearshore, bottom, salinity measurements in about 10 m water depths offshore from the Sagavanirktok River (see Figure 4-9 for mooring locations) reveal bottom water salinities as low as 14 ppt early in the spring melt and freshet period (Weingartner et al. 2005). During breakup the bottom water salinity drops from greater than 30 ppt over a period of about 1 week at the beginning of August to as low as 15 ppt and then climbs back up to 30 by the end of August as the surface lens of fresh water is mixed down into the water layer. Figure 4-10 shows the measured bottom water salinity in about 7 m of water at the Dinkum mooring. These measurements confirm the presence of the surface fresh water lens and its eventual influence on water salinity at depth.



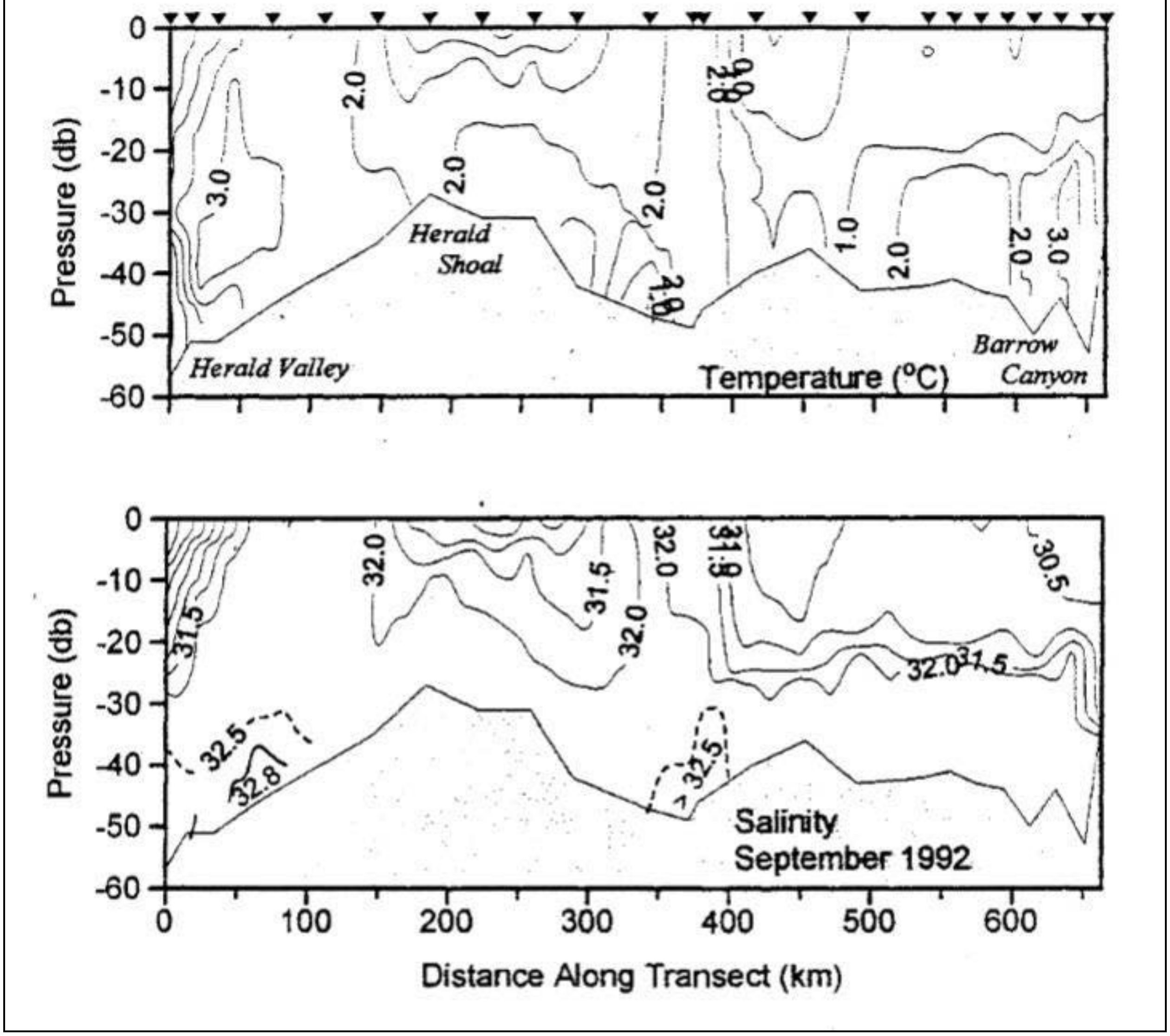
Source: Weingartner 1998 Figure 2

Figure 4-1 Location of Temperature and Salinity Measurements Reported in Figure 1-2



Source: Weingartner 1998 Figure 8

Figure 4-2 Seasonal Temperature and Salinity Variation on the Chukchi Shelf



Source: Weingartner 1998 Figure 11

Figure 4-3 Salinities and Temperatures Along an E-W Transect in the Chukchi Sea (Wrangel Is to Barrow)

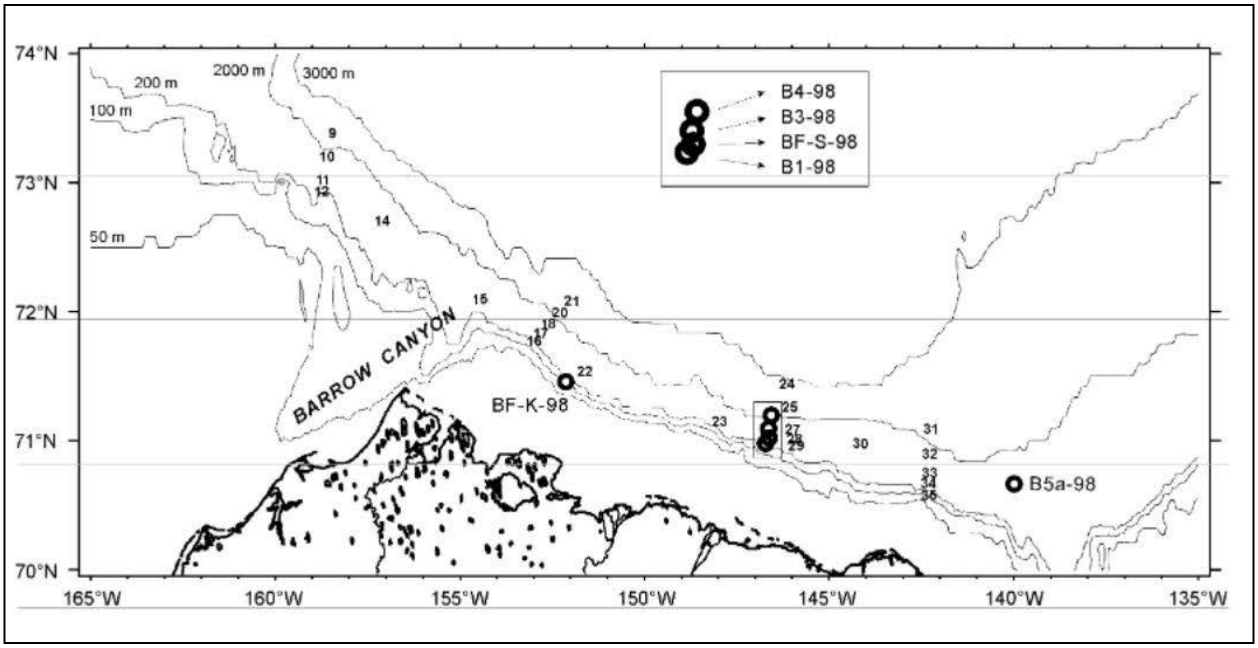


Figure 4-4 Mooring and Hydrographic Station Locations (source: Weingartner 2006 Figure 7)

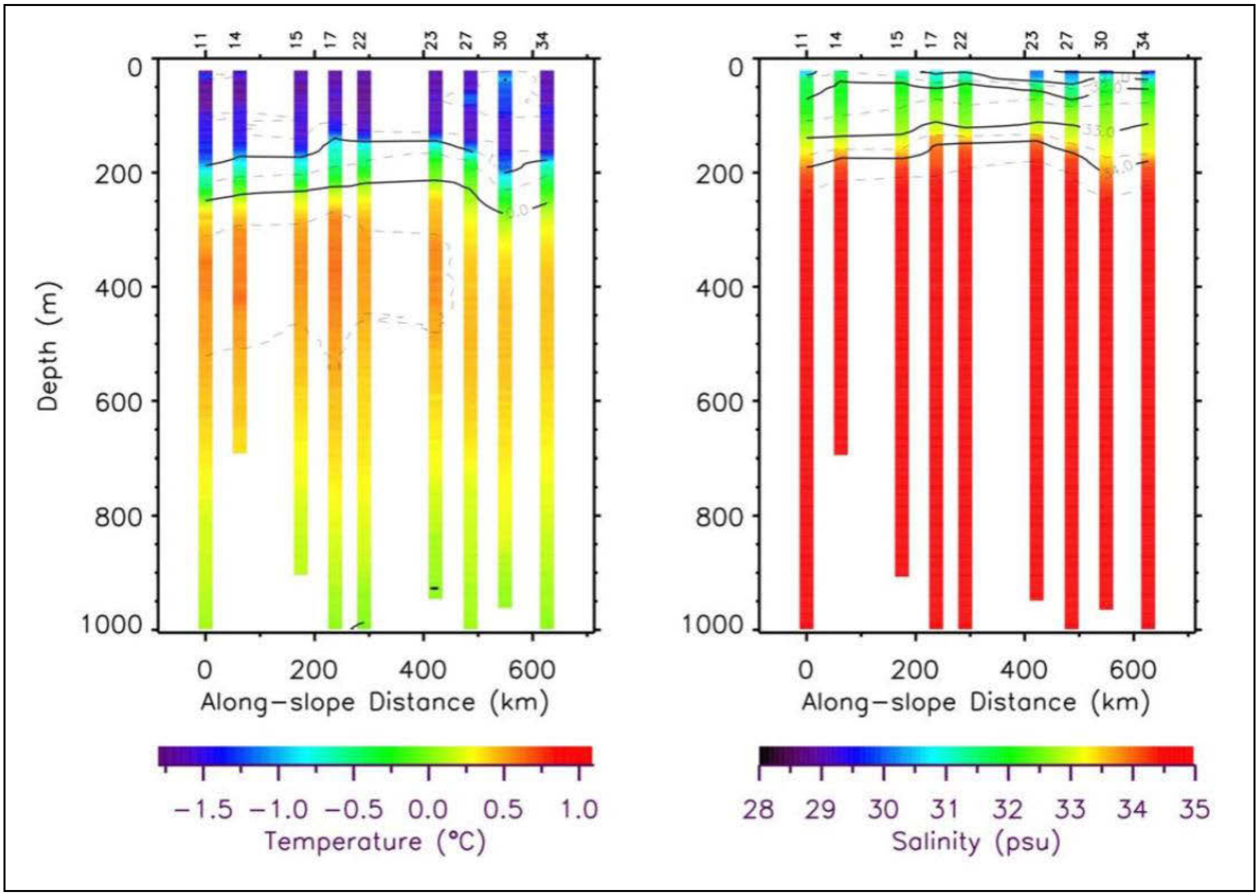


Figure 4-5 Salinity and Temperature Measurements Along Alaskan BS Slope (source: Weingartner 2006 Figure 36)

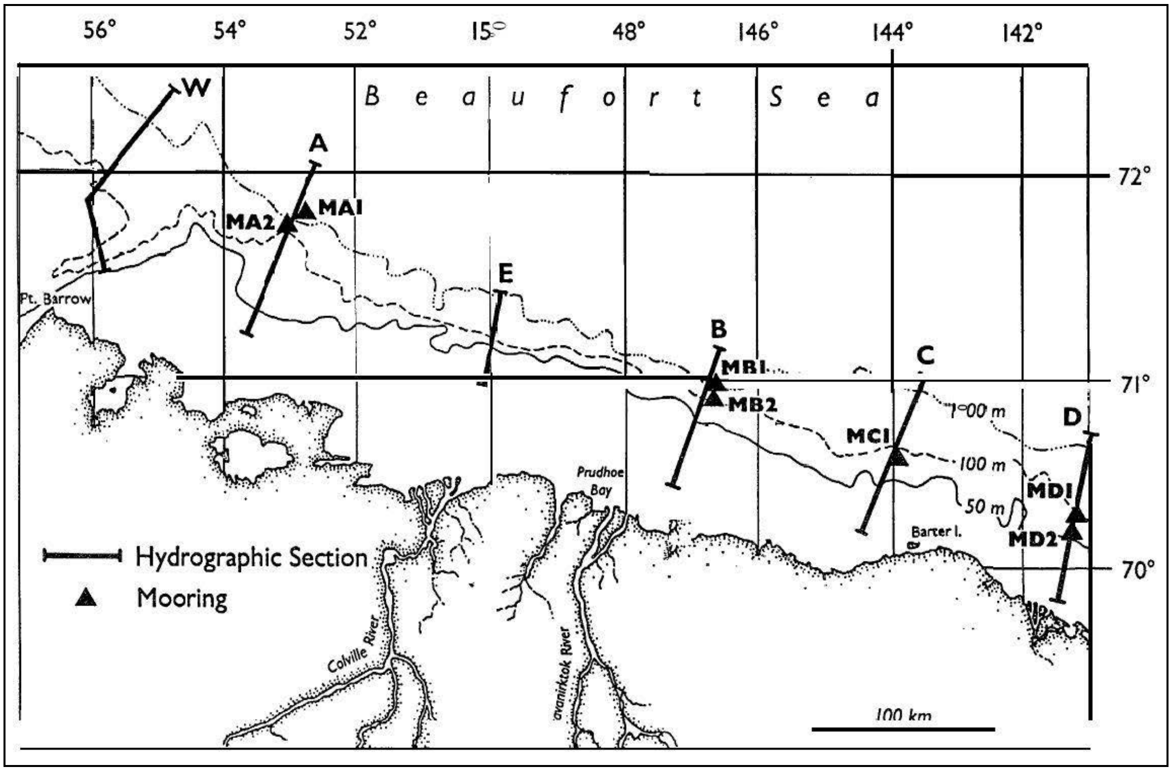


Figure 4-6 October Measurement Transects and Mooring Locations (source: Aagaard 1988 Figure 1)

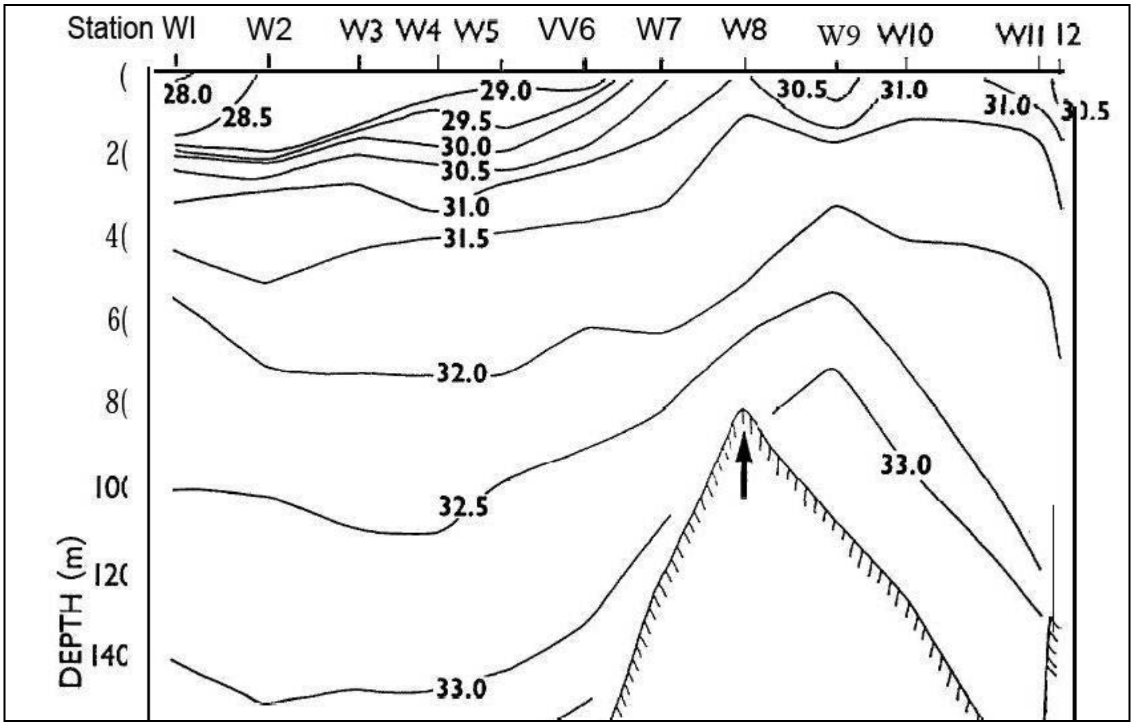


Figure 4-7 October 1988 Water Salinities at Transect W (source: Aagaard 1988 Figure 8)

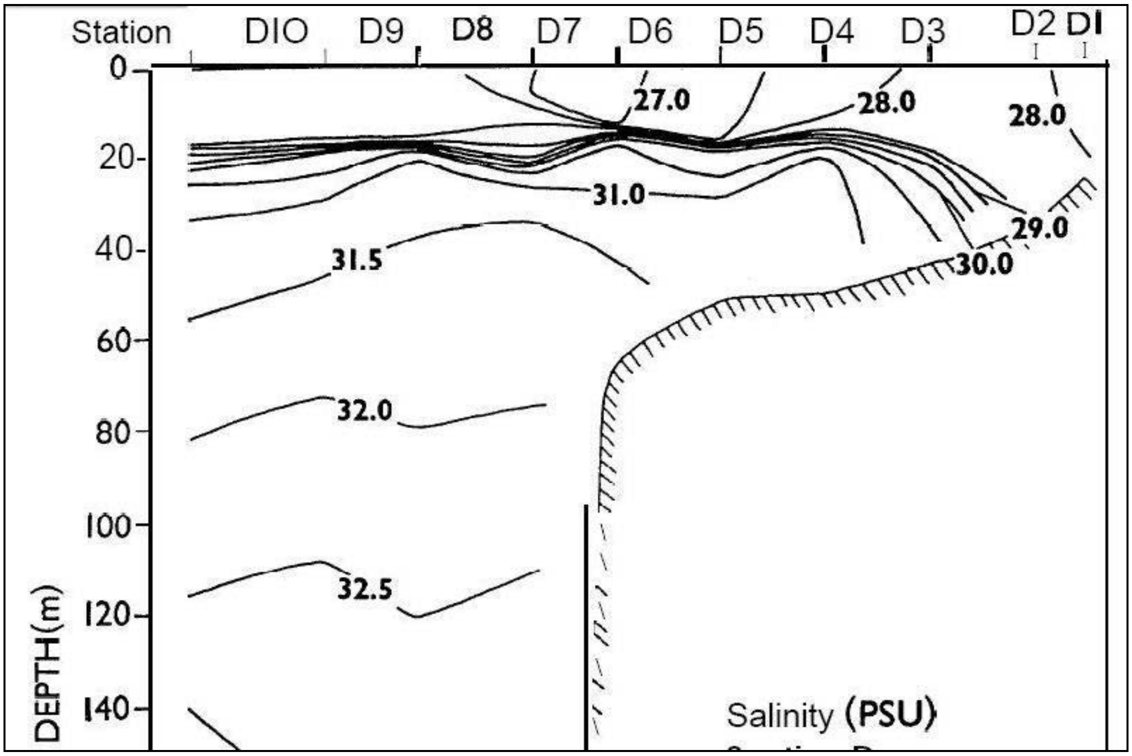


Figure 4-8 October 1988 Water Salinities at Transect D (source: Aagaard 1988 Figure 53)

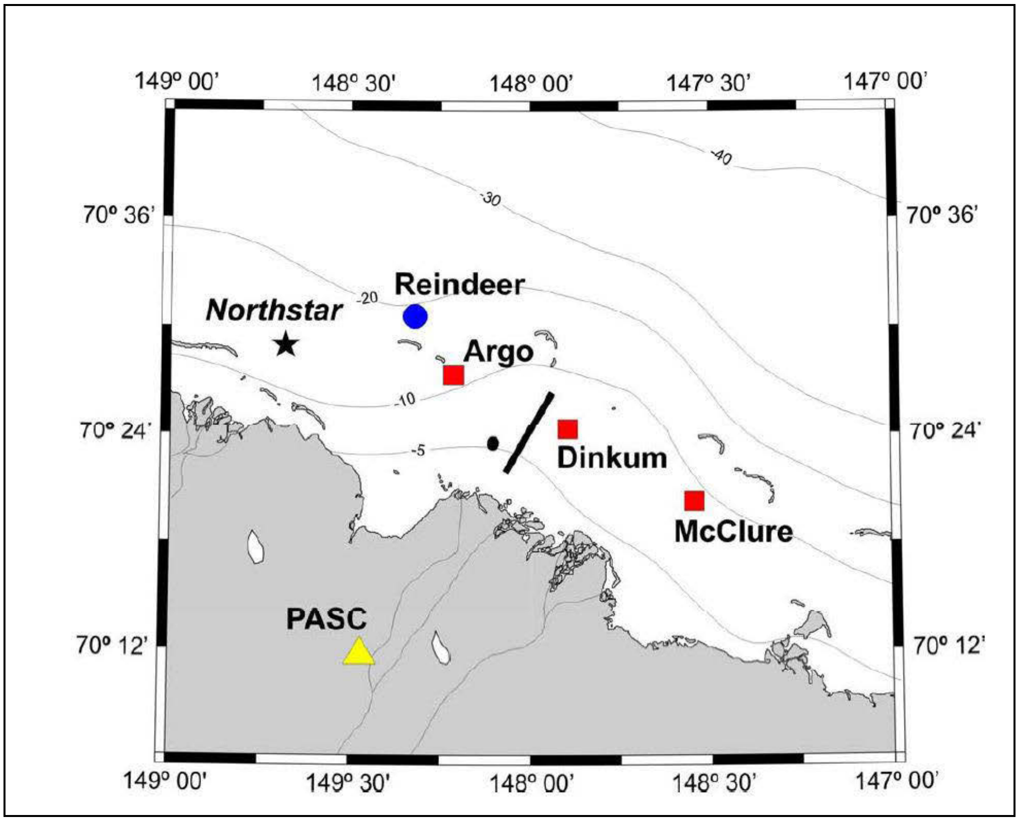


Figure 4-9 Nearshore Instrument Locations (source Weingartner et al. 2005)

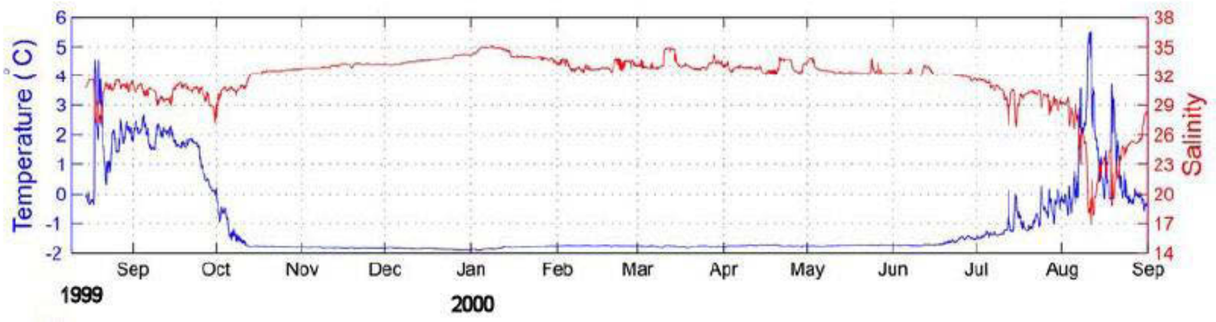


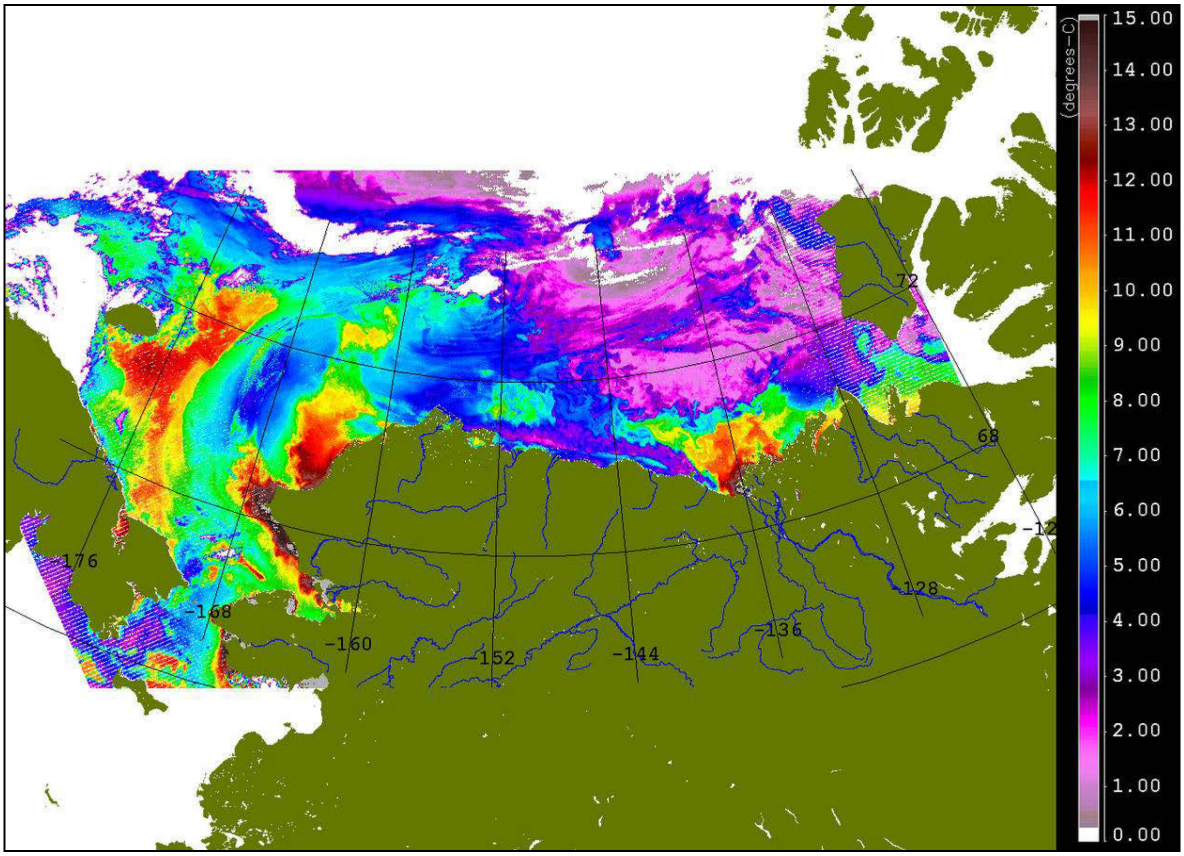
Figure 4-10 Nearshore Water Salinity in Beaufort Sea at Dinkum Deployment (source: Figure 45 Weingartner et al. 2005)

4.2 Water Temperature

The dispersibility of a crude oil is a strong function of its viscosity, which in turn is often very temperature dependent. As crude oils cool their viscosities increase and with increasing viscosities there is a potential for the reduction of dispersant effectiveness. If the water temperature is below the pour point of the oil (and the oil's temperature has reached the water temperature) the oil may not be fluid and is very viscous. Under these conditions the dispersant does not easily mix with the oil when applied. As a result of the combination of the poor mixing of the dispersant into the oil and the high viscosity of the oil dispersants are not effective at these temperatures. The chemical dispersibility of the crude oil is affected by the temperature only as it affects the viscosity of the oil. The oil's viscosity is affected by the water temperature on which it sits and during sunny days by the heating of the surface of the oil by the sun. Different crude oils can have very different viscosities at the same temperature and many can be quite fluid at temperatures near freezing. There is really no water temperature that will completely restrict the use of chemical dispersant. The oil viscosity – temperature relationship must be considered for each candidate oil before an evaluation of the potential for dispersant effectiveness can be made.

The surface water temperatures in the Chukchi and Beaufort Seas in the open water seasons can vary from close to freezing (-2 °C) to upwards of 10 °C. Figure 4-2, Figure 4-3, Figure 4-5, and Figure 4-10 all show surface water temperatures in the Chukchi and Beaufort Seas that fall with this range. The satellite image in Figure 4-11 shows August surface water temperatures in the US Beaufort Sea ranging from 2 to 9 °C and in the Chukchi Sea from 4 to 14 °C with considerable spatial variability in both regions. The wide spatial variation in surface water temperatures in both the Chukchi and Beaufort Seas can be seen in the extensive imagery catalogued at http://mather.sfos.uaf.edu/~mschmidt/ims_summary_new.html.

The decision to use dispersants from a potential effectiveness standpoint in these regions will require a case-by-case evaluation of the prevailing water temperature and the oil viscosity-temperature relationship.



Source: http://mather.sfos.uaf.edu/~mschmidt/ak_beaufort_sea_2007/ims_beaufort_aug_2007.html.

Figure 4-11 August 22, 2007 MODIS sea surface temperature image of the Chukchi Sea and Beaufort Sea

4.3 Ice Cover

The presence of greater than 9/10ths ice cover eliminates the possibility of using conventional surface applied dispersant operations. The presence of the ice either encapsulates the oil making it impossible to target with aerial applied dispersant or dampens the surface energy such that there is insufficient energy to break the oil into droplets once treated. In ice conditions with less than 3/10ths cover chemical dispersants will perform much the same as in open water conditions since the surface mixing energy is not overly dampened by the presence of the ice. The performance of dispersants in 3/10ths to 8/10ths ice cover without additional mixing energy applied is somewhat uncertain. Research suggests that performance may be enhanced in these conditions by the energy generated at the ice edge as the ice pieces jostle even under low wave energy (SL Ross 2002, 2006a). Additional research on the potential for dispersant use under partial ice cover conditions is currently being considered (OGP 2014). Regardless, it is instructive to identify the potential periods of open water when traditional surface dispersant application operations could be successful. In the Chukchi Sea region open water periods can exist in the months from June through November depending on the year based on an assessment of the US National Snow and Ice Data Center's archived ice cover data located at the following URL: (http://nsidc.org/data/seaice_index/archives/image_select.html). Open water is most common in the months of July through October in this region but the shoulder months of June and November may present dispersant application opportunities depending on the ice year. In the Beaufort Sea region the maximum likely extent for open water dispersant use is from July to October with the more likely season being from August to October. Table 4-1 shows the months when the two regions were primarily in open water or low ice concentration conditions for the years from 1998 to 2013.

Table 4-1 Open Water period in US Chukchi and Beaufort Sea Regions

Year	Chukchi Sea Open Water Months	Beaufort Sea Open Water Months
1998	July, Aug., Sept., Oct., Nov	~~July~~, Aug., Sept., Oct.
1999	July, Aug., Sept., Oct.	Aug., Sept., ~~Oct.~~
2000	July, Aug., Sept., Oct., ~~Nov~~[1]	Aug., Sept., Oct.
2001	July, Aug., Sept., Oct.	~~Aug.~~, Sept.
2002	~~June~~, July, Aug., Sept., Oct., Nov	Aug., Sept., Oct.
2003	June, July, Aug., Sept., Oct., Nov	Aug., Sept., Oct.
2004	July, Aug., Sept., Oct., ~~Nov~~	Aug., Sept., Oct.
2005	~~June~~, July, Aug., Sept., Oct., ~~Nov~~	Aug., Sept., Oct.
2006	July, Aug., Sept., Oct., Nov	Aug., Sept., Oct.
2007	~~June~~, July, Aug., Sept., Oct., ~~Nov~~	Aug., Sept., Oct.
2008	July, Aug., Sept., Oct.	~~July~~, Aug., Sept., Oct.
2009	July, Aug., Sept., Oct.	July, Aug., Sept., Oct.
2010	July, Aug., Sept., Oct., ~~Nov~~	Aug., Sept., Oct.
2011	~~June~~, July, Aug., Sept., Oct.	Aug., Sept., Oct.
2012	July, Aug., Sept., Oct.	Aug., Sept., Oct.
2013	July, Aug., Sept., Oct.	Aug., Sept., Oct.
[1] Crossed out months had partial open water in the region		
Source: imagery at http://nsidc.org/data/seaice_index/archives/image_select.html		

An additional source of information on ice cover for the central Chukchi Sea area is Figure 4-12. This shows the open water and ice cover conditions for the Burger drilling prospect from 1995 to 2011. The results are similar to the general trends identified in Table 4-1.

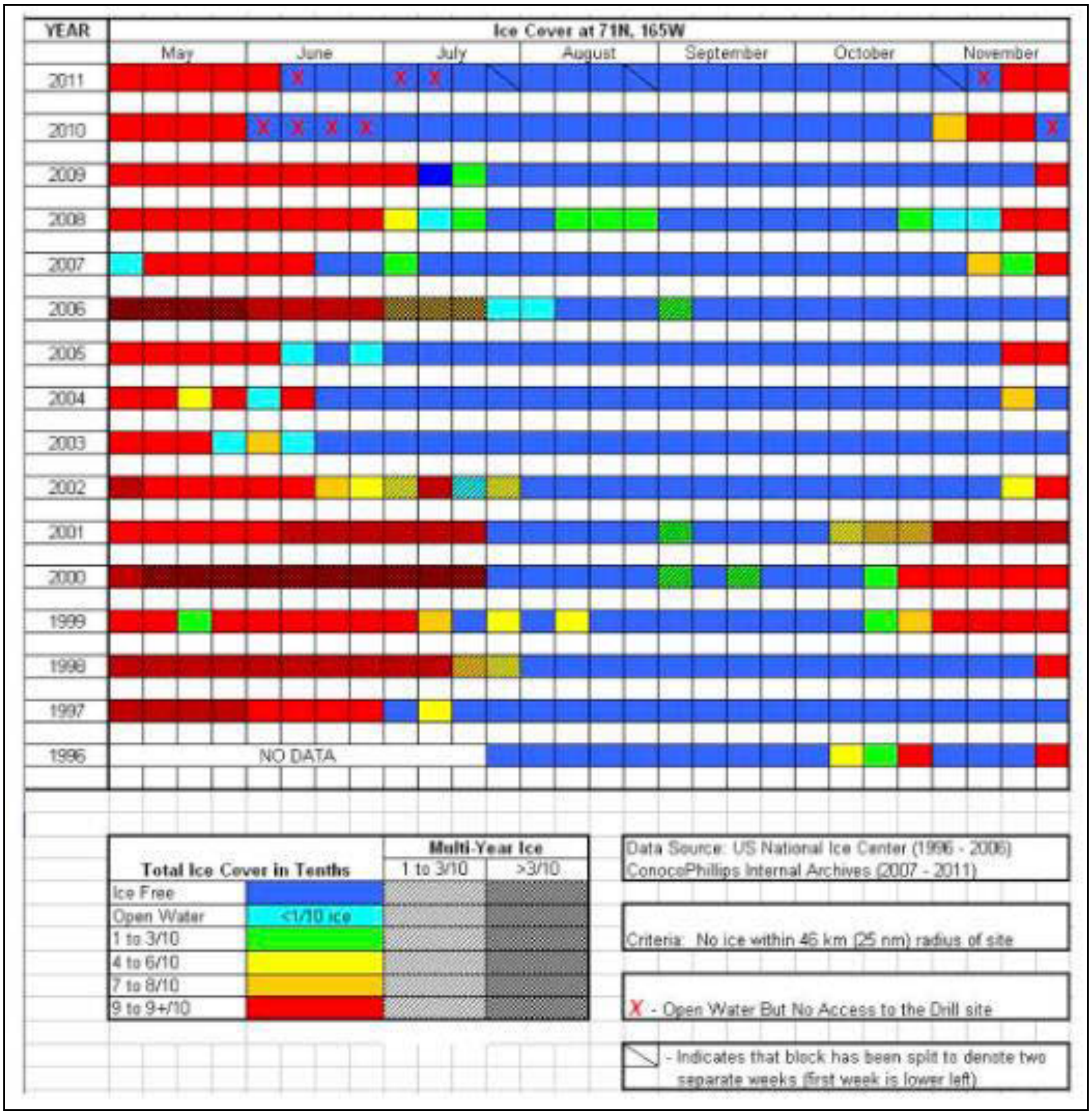
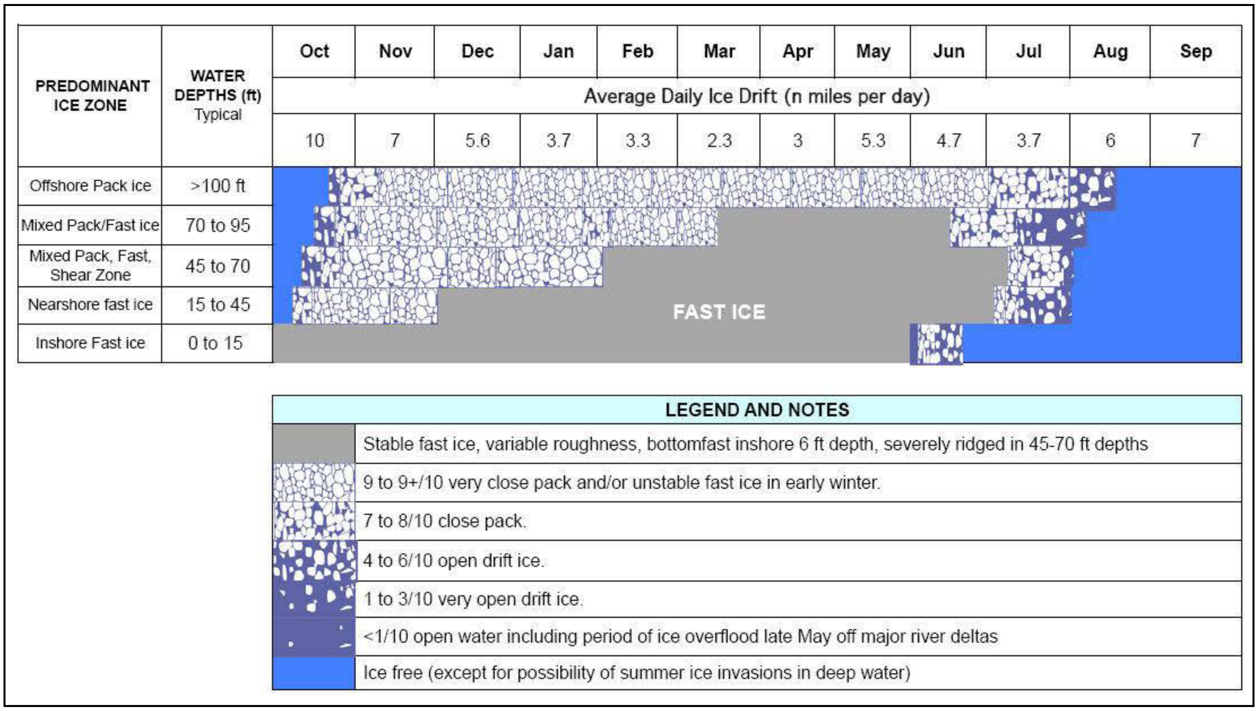


Figure 4-12 Ice Cover at Burger prospect in Central Chukchi Sea (source: Wang et al. 2012)

An additional source of information on ice cover for the US Beaufort Sea north of Point Thompson around Shell's Sivulliq drilling prospect is Figure 4-13. This shows the typical open water and ice cover conditions for the Shell's Sivulliq drilling prospect. The results are similar to the general ice cover trends for the Beaufort Sea Region identified in Table 4-1.



PREDOMINANT ICE ZONE	WATER DEPTHS (ft) Typical	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
		Average Daily Ice Drift (n miles per day)											
		10	7	5.6	3.7	3.3	2.3	3	5.3	4.7	3.7	6	7
Offshore Pack ice	>100 ft												
Mixed Pack/Fast ice	70 to 95												
Mixed Pack, Fast, Shear Zone	45 to 70												
Nearshore fast ice	15 to 45												
Inshore Fast ice	0 to 15												

LEGEND AND NOTES	
■	Stable fast ice, variable roughness, bottomfast inshore 6 ft depth, severely ridged in 45-70 ft depths
▨	9 to 9+/10 very close pack and/or unstable fast ice in early winter.
▨	7 to 8/10 close pack.
▨	4 to 6/10 open drift ice.
▨	1 to 3/10 very open drift ice.
▨	<1/10 open water including period of ice overflood late May off major river deltas
■	Ice free (except for possibility of summer ice invasions in deep water)

Figure 4-13 Ice Cover at Sivulliq prospect north of Point Thompson in the Beaufort Sea (source: Dickins 2007)

In periods of complete ice cover dispersants could be used in conjunction with ice-breaker support and the application of additional mixing energy through the azimuthal stern drive propeller systems deployed by modern icebreakers (SL Ross 2005, 2006a, 2006c). Subsea dispersant injection during a subsurface well blowout is another type of dispersant operation that could be conducted in a complete ice cover environment. Dispersant effectiveness and net environmental benefit considerations would have to be evaluated on a case- by-case basis before implementing these types of operations.

4.4 Wave Energy

Long term historical wave height data is not available in the U.S. Chukchi and Beaufort Sea regions. A few recent years of wave data at specific locations are available from summer buoy deployments (see http://www.aoos.org/aoos-data-resources) but this data is insufficient both temporally and spatially to quantitatively assess the potential for dispersant effectiveness in the region. Long term wind data are, however, available for the region through shore-based weather stations and offshore hindcast analyses. Wave heights can be derived from wind speed data through the Beaufort wind scale in the absence of actual measured wave height data and that approach has been taken to estimate wave heights for this project. The Beaufort scale is provided in Table 4-2. The wave height and wind speed data from this table have been plotted in Figure 4-14 to develop a polynomial prediction of wave height as a function of wind speed.

Table 4-2 Beaufort Wind Scale

Force	Wind (Knots)	WMO Classification	Appearance of Wind Effects	
			On the Water	On Land
0	Less than 1	Calm	Sea surface smooth and mirror-like	Calm, smoke rises vertically
1	1-3	Light Air	Scaly ripples, no foam crests	Smoke drift indicates wind direction, still wind vanes
2	4-6	Light Breeze	Small wavelets, crests glassy, no breaking	Wind felt on face, leaves rustle, vanes begin to move
3	7-10	Gentle Breeze	Large wavelets, crests begin to break, scattered whitecaps	Leaves and small twigs constantly moving, light flags extended
4	11-16	Moderate Breeze	Small waves 1-4 ft. becoming longer, numerous whitecaps	Dust, leaves, and loose paper lifted, small tree branches move
5	17-21	Fresh Breeze	Moderate waves 4-8 ft taking longer form, many whitecaps, some spray	Small trees in leaf begin to sway
6	22-27	Strong Breeze	Larger waves 8-13 ft, whitecaps common, more spray	Larger tree branches moving, whistling in wires
7	28-33	Near Gale	Sea heaps up, waves 13-19 ft, white foam streaks off breakers	Whole trees moving, resistance felt walking against wind
8	34-40	Gale	Moderately high (18-25 ft) waves of greater length, edges of crests begin to break into spindrift, foam blown in streaks	Twigs breaking off trees, generally impedes progress
9	41-47	Strong Gale	High waves (23-32 ft), sea begins to roll, dense streaks of foam, spray may reduce visibility	Slight structural damage occurs, slate blows off roofs
10	48-55	Storm	Very high waves (29-41 ft) with overhanging crests, sea white with densely blown foam, heavy rolling, lowered visibility	Seldom experienced on land, trees broken or uprooted, "considerable structural damage"
11	56-63	Violent Storm	Exceptionally high (37-52 ft) waves, foam patches cover sea, visibility more reduced	
12	64+	Hurricane	Air filled with foam, waves over 45 ft, sea completely white with driving spray, visibility greatly reduced	

Source: http://www.spc.noaa.gov/faq/tornado/beaufort.html

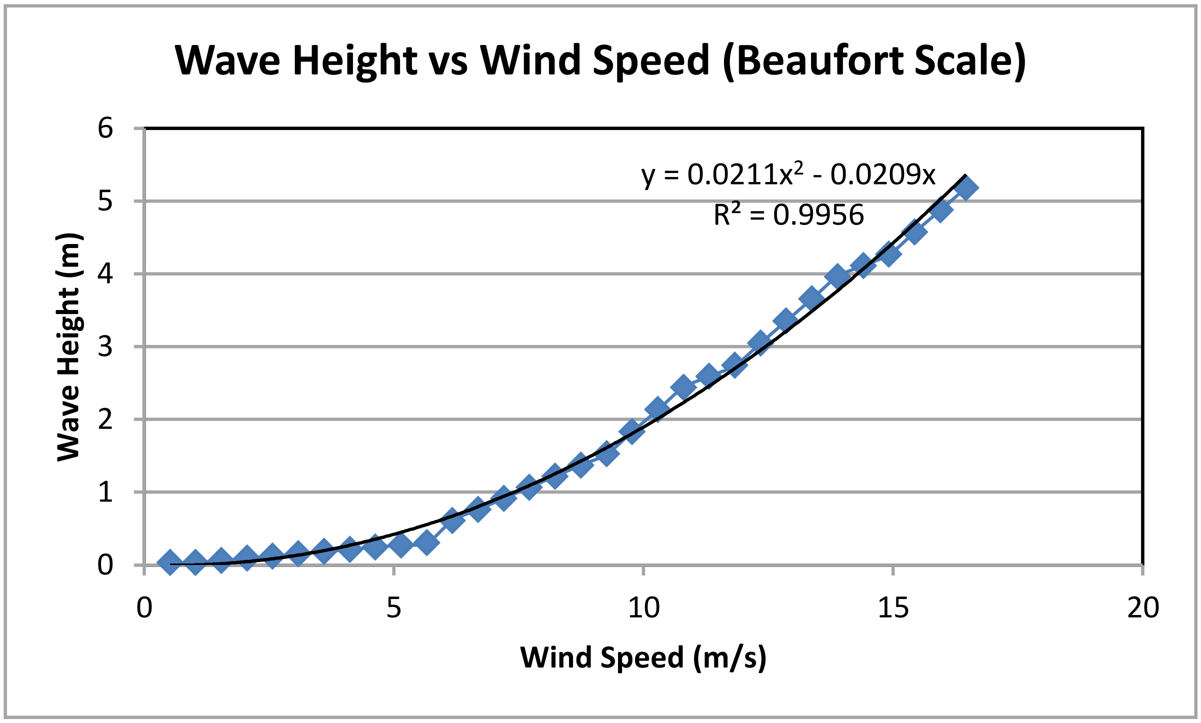


Figure 4-14 Beaufort Wind Scale Wave height Wind Speed Correlation

Land based weather station data were acquired from NOAA for a number of locations along the Chukchi and Beaufort coast lines and these data sets were evaluated for use in the project. Unfortunately, the weather station data had significant data gaps over the past 10 years of data and was not of sufficient quality for use in this project. Fortunately, the Bureau of Ocean Energy Management (BOEM) funded a project to develop a hindcast wind data set for the U.S. Chukchi and Beaufort Sea regions that spans the 31 year period from 1979 to 2009. The data set is known as CBHAR (Chukchi/Beaufort High-resolution Atmosphere Reanalysis). Hourly, ten meter data from five grid points from the BOEM data set have been acquired for this project for use in estimating wave heights in the region. Locations of the offshore grid points selected for analysis are provided in Table 4-3. These locations are mapped in Figure 4-15.

Table 4-3 BOEM Hindcast Wind Data Grid Point Locations

Station Identifier	Longitude	Latitude	Nearby Land Weather Station
Station1	-167.5	69.0	Cape Lisbourne
Station2	-166.0	71.0	Wainwright
Station3	-156.0	72.0	Barrow
Station4	-148.0	71.0	Prudhoe Bay
Station 5	-140.0	70.0	Barter island

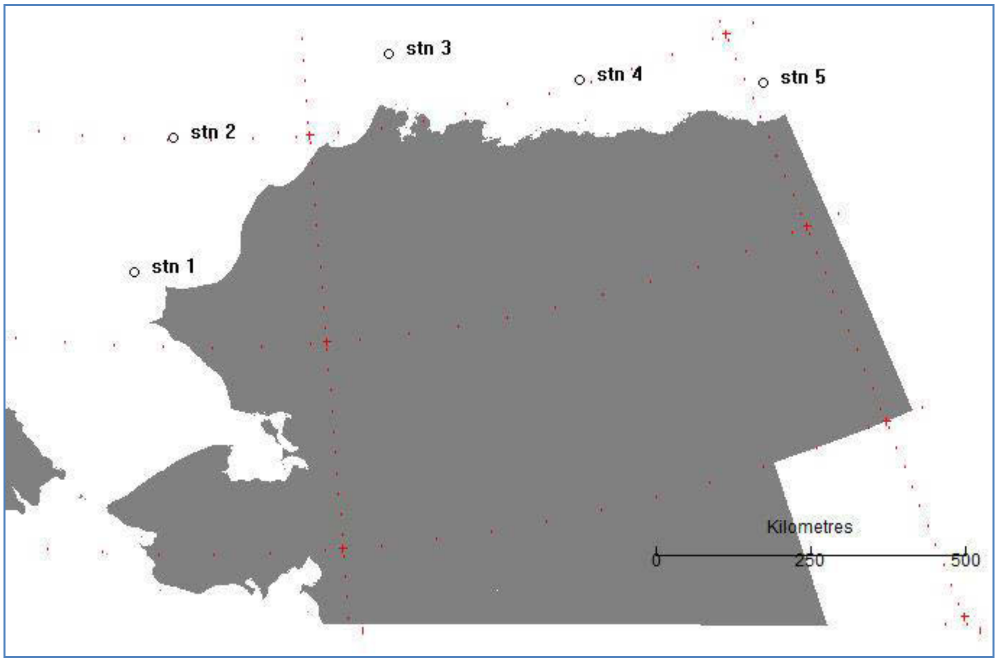


Figure 4-15 Hindcast Wind Grid Point Locations

The Beaufort wind-wave height correlation from Figure 4-14 has been applied to the BOEM hindcast wind data to provide wave height estimates for use in dispersant effectiveness evaluation across the region. The criteria in Table 4-4 have been used to define the times when aerial chemical dispersant application by large aircraft would be possible based on prevailing wind speeds and likely effective based on wave conditions and ice cover. These criteria were established for use in a dispersant use GAP analysis (SL Ross 2011). The rationale for the selection of these criteria is as follows.

Dispersants can be applied by large aircraft until wind speeds are high enough to impair the dispersant spraying operation. At speeds greater than 15 m/s large aircraft have difficulty maintaining their spray path and the high winds affect the dispersant fallout (Exxon 2000). Dispersants are most effective when slicks of fresh or lightly weathered oils can be sprayed with an adequate dose of effective dispersant product in the presence of breaking waves. In offshore environments breaking waves develop when wind speeds exceed 3.5 to 5.4 m/s and waves are 0.5 to 1 m in height. Dispersants can be applied in non-breaking wave conditions, where dispersion might not occur immediately, if breaking waves are likely to occur within a reasonable time after dispersant application. Research has shown that dispersants applied to slicks on calm seas will cause effective dispersion if the treated slicks are exposed to breaking waves within 48 hours (Lewis, et al. 2010). Dispersant effectiveness begins to be impaired at wave heights of 3 m and above, as at this point waves begin to entrain a considerable proportion of the slick into the water and hold it in suspension temporarily, making it difficult to hit the oil with dispersant spray.

Table 4-4 Operating Limits for Large Aircraft Dispersant Operations

Aerial Dispersant Application (large aircraft)	Favorable	Marginal	Not Possible
Wind Speed (m/s)	<13	>=13 to <=15	>15
Wave Height (m)	>0.6 and <3.0 OR >0.0 and <3.0 if >=0.6 in following 48 h	>=3.0 and <=4.6	> 4.6 OR <0.6 if <0.6 in following 48 h
Ice Cover (10^{ths})	<5/10	5/10 to 9/10	>9/10

The conditions identified in Table 4-4 were applied to the hourly hindcast wind data (and wave heights estimated using the correlation in Figure 4-14) over the full 31 years of data and for the past 10 years to determine the percentage of time that aerial dispersant applications could be effective. Table 4-5 summarizes the results of this assessment for wind station 1. The results for the assessment over the past 10 years (columns 5, 6 and 7) are very similar to the full 31 year analysis (columns 2, 3 and 4) with a maximum of a few percent difference in any given month. Based on this assessment chemical dispersant use would be favorable for 80 to 90% of the time at this location. This does not account for other operational limitations such as visibility and daylight hours as this was out of the scope of the study. Detailed tables for the remaining wind stations are provided in Appendix A.

Table 4-5 Percentage of Time Dispersants Would Be Effective at Wind Station 1 (Chukchi Sea Offshore Cape Lisbourne)

Percent of Time Dispersants Effective (48 hour Calm Wind Grace Period)						
	31 year Data Analysis (1979 to 2009)			10 year Data Analysis (2000 to 2009)		
Month	Favorable	Impaired	Not Favorable	Favorable	Impaired	Not Favorable
1	0	0	100 (ice covered)	0	0	100 (ice covered)
2	0	0	100 (ice covered)	0	0	100 (ice covered)
3	0	0	100 (ice covered)	0	0	100 (ice covered)
4	0	0	100 (ice covered)	0	0	100 (ice covered)
5	0	0	100 (ice covered)	0	0	100 (ice covered)
6	80	3	17	78	3	19
7	87	3	10	87	3	10
8	90	4	5	87	4	9
9	86	8	6	91	5	4
10	82	13	5	82	13	6
11	78	13	9	81	12	7
12	0	0	100 (ice covered)	0	0	100 (ice covered)

Table 4-6 shows the percentage of time that dispersants would be favorable for all 5 of the wind stations based on the most recent 10 years of data (column 5 from the detailed table results). For the months of July through October, where data exists for all wind stations, the least variability in the results occurs in September where favorable conditions across both regions range from 87 to 91%. The highest variability for these months is in July where favorable conditions range from 71 to 87%, with the Beaufort Sea region having the lowest percent of time with favorable conditions.

Table 4-6 Percentage of Time Dispersants Would Be Favorable Based on 10 Year Data Analysis: All Wind Stations

Month	Percent of Time Dispersant Effective (48 hr Calm Wind Grace Period)						
	10 Year Data Analysis (2000 to 2009): Favorable						
	stn 1	stn 2	stn 3	stn 4	stn 5	Average	Std. Dev.
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	78	77	0	0	0	77	1
7	87	83	76	71	81	80	6
8	87	87	79	75	78	81	5
9	91	90	87	87	87	88	2
10	82	88	86	84	79	84	4
11	81	82	0	0	0	81	1
12	0	0	0	0	0	0	0

5 Historical Dispersant Effectiveness Testing on Alaskan Oils and Identification of Knowledge Gaps

This section summarizes the results of past chemical dispersant effectiveness studies that have been conducted on Alaskan oils for use in dispersant use decision-making. The extensive libraries of Environment Canada and SL Ross Environmental research Ltd., the Arctic and Marine Oil Spill Technical Seminar (AMOP), the International Oil Spill Conference Proceedings (IOSC), the Louisiana Universities Marine Consortium (LUMCON) library and other scientific Journals have been searched for this purpose.

5.1 Spill Related Properties of Alaskan Oils

The physical properties of a number of Alaskan production and pipeline oils are provided in Table 5-1 to show the range of oils that have been found in Alaska to date. A study of the change in the properties of the ANS blend that has been transported via the Alyeska pipeline over the past 30 years has also been recently conducted (SL Ross 2013). This study shows that the pipeline oil has progressively become less dense, less viscous and less likely to form stable emulsions. See Figure 5-1 and Figure 5-2. These property changes result in oil that is likely more amenable to chemical dispersion. The change in property is due to a change in the percentage of each production field’s contribution to the total flow and possibly due to a change in the properties of the individual field oils themselves. Not enough data has been collected on the properties of the individual field crude oils to track their property changes over time. This information is provided to demonstrate that results from dispersant effectiveness tests conducted on a Prudhoe Bay pipeline crude in the 80’s may not be comparable to effectiveness tests completed on Alaska North Slope crude in the 2000’s due to different oil composition.

Table 5-1 Alaskan Oil Physical Properties

Oil Name	Density (g/cc) @ 15 °C			Viscosity (cP) @15 °C			Pour Point (°C)		
	fresh	2-day	2-week	fresh	2-day	2-week	fresh	2-day	2-week
ANS Blend (2004)[1]	0.870	0.920	0.930	10.2 (0%)	164 (30.8%)	374 (38.2%)	-21	3	9
ANS Blend (2012)	0.874	0.923	0.937	14 (0%)	156 (27%)	505 (35%)	<-18	-6	0
Endicott (2004)[1]	0.921	0.924	0.925	205 (0%)	247 (0.8 %)	342 (5.3%)	12	15	15
Kuparuk (2004)[1]	0.920	0.943	0.956	81 (0%)	351 (9.5%)	1391 (20.3 %)	<-21	<-21	-9
Lisbourne (1994)[2]	0.875	0.906	0.923	15.9 (0%)	187 (21.1%)	327 (30.6%)	-3	7	15
Northstar(2004)[1]	0.821	0.868	0.877	2.1 (0%)	14.4 (43.7%)	24.4 (52%)	<-21	0	3
Pt. McIntyre (1994)[2]	0.895	0.911	0.920	44 (0%)	125 (9.8%)	441 (18%)	-4	3	11

[1] OCS Study MMS 2008-033 Empirical Weathering Properties of Oil in Ice and Snow, Project Number 1435-01-04-RP-34501 (Mar Inc. 2008)

[2] Spill Related Properties of Fresh and weathered Alaskan Crude Oils (SL Ross 1994)

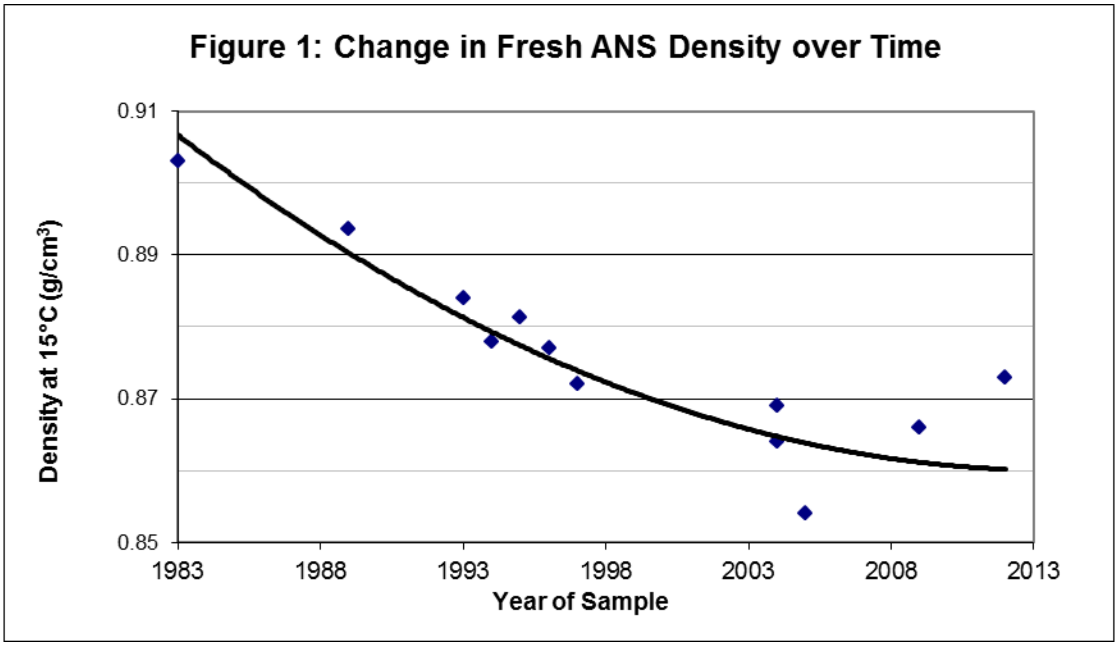


Figure 5-1 Change in Fresh ANS Density over Time

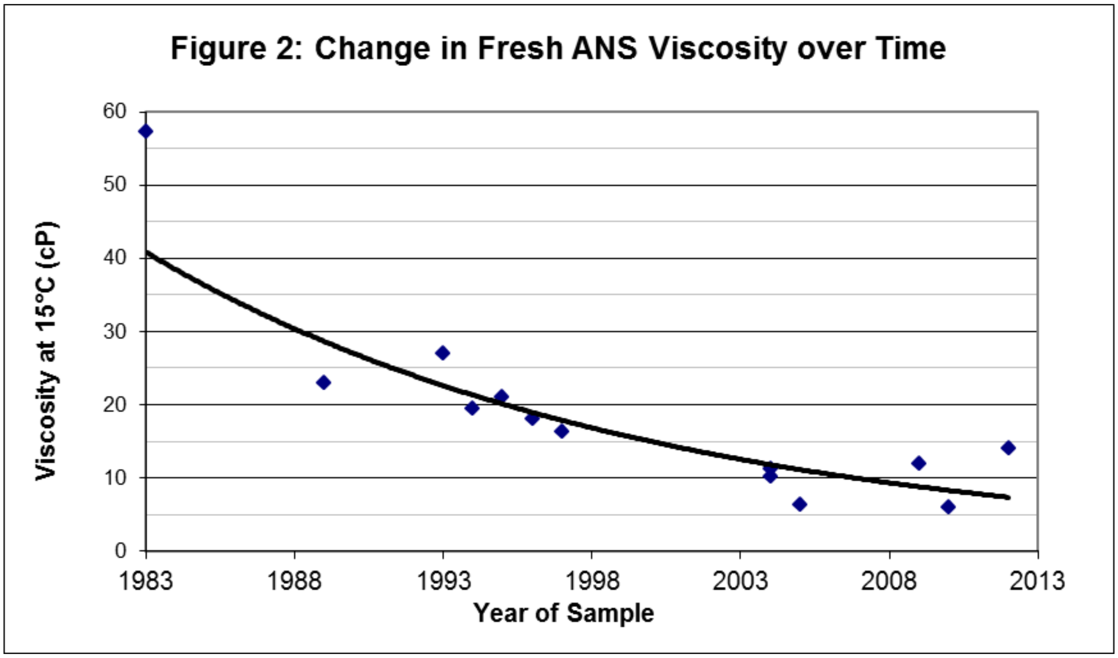


Figure 5-2 Change in Fresh ANS Viscosity over Time

5.2 Background - Mechanisms of Chemical Dispersion

When spilled on water, oil exhibits a cohesiveness or resistance to break up. This cohesive strength is due to the interfacial tension or contractile skin between the oil and water. A chemical dispersant sprayed onto an oil slick acts at the oil-water interface to reduce this interfacial tension. This action promotes the break-up of the oil film into droplets that disperse into the water phase. If the droplets are small enough they will have little buoyancy and will be carried away and diluted by normal ocean current and movement.

Surface active agents (surfactants) are the key components of a chemical dispersant. These compounds contain both a water compatible and an oil compatible group. Because of this molecular structure, the surfactant locates at the oil-water interface, reduces the interfacial tension, and thereby enables the oil slick to break up into finely dispersed oil droplets with the addition of significantly less energy than in the absence of the dispersant. Mackay and Hossain (1982) estimated that a concentration at an oil/water interface of 1 volume of dispersant per 500 volumes of oil will cause a 20-fold reduction in interfacial tension, say, from 20 dynes/cm to 1 dyne/cm. Since dispersants are normally applied at a ratio of 1 volume of dispersant to 20 volumes of oil, the implication is that only a few percent of the dispersant is being effective at any time, most being present in the bulk of the oil and thus remote from the interface.

Despite the great decrease in interfacial tension, some mixing energy is needed to promote movement and dispersion of the fine oil droplets into the water column. This energy can be supplied either by the natural motion and currents of the sea or by mechanical means such as work boats. The greater the available energy, the less dispersant or less effective dispersant is required.

A dispersant formulation also contains a solvent. Since many of the surface agents used in oil spill dispersant formulations are viscous, some form of solvent is necessary to reduce viscosity so that the mixture may be properly applied by conventional spray equipment. In addition, the solvent may act to depress the freezing point for low temperature usage and to enhance the mixing/penetration of the surfactant(s) into more viscous oils. In general, present day surfactants have demonstrated very low toxicity. In addition, these current formulations have substituted dearomatized hydrocarbons or aqueous solvents, resulting in very low toxicity dispersant formulations as compared with early formulations.

By their very nature, present-day dispersants include active ingredients that are more soluble in water than in oil. So the dispersant must be applied directly to the oil; otherwise the chemical will be lost to the water phase. Even when applied directly to the oil the chemicals will leach into the water, but the rate at which this happens is not well understood. Most products contain so-called "anionic" surfactants, like sulphosuccinates, in combination with "non-ionic" surfactants, like sorbitan ester surfactants (the SPANS® family of surfactants) and polyethoxylated sorbitan ester surfactants (the TWEEN® family). Studies on the subject (Knudsen et al. 1994, Hokstad et al. 1996) indicate that anionic surfactant compounds will rapidly leach into water, but that the rate of leaching of the non-ionic compounds is uncertain and dependent on a number of factors. Clearly, the leaching process is a complicated one, and it can be assumed that certain components of modern dispersant products will gradually leach from a layer of crude oil into the underlying water column and negatively affect the dispersibility of the oil. Tests conducted at Ohmsett demonstrated that under calm conditions enough dispersant remained with a treated oil slick to still be effective 2 to 6 days of exposure depending on the drift speed of the slick over the water surface and the exposure of the underside of the slick to surfactant free water (SL Ross 2007, 2008). This suggests that an oil spill can be dosed in relatively calm conditions with the expectation that the dispersant will remain with the oil and become effective when sea states and mixing energies increase after a few days.

5.3 Dispersant Effectiveness Test Results on Alaskan Oils

A review of scientific literature on the results of chemical dispersant effectiveness tests, specifically conducted on Alaskan crude oils, has been undertaken. Research that investigated chemical dispersant effectiveness under arctic conditions and in the presence of ice using other oil types has also been included in the review due to paucity of research in this area. Table 5-2 identifies the literature that has been reviewed and identifies the key variables that were studied in each test series. The review has focused on the parameters that could affect dispersant performance that are of specific concern to the arctic environment. These parameters include the test temperature, the water salinity, the mixing energy and the presence of ice. Oil type, dispersant type and dispersant dosage have also been considered in this review. With a few exceptions, only tests that have used Alaskan oil have been reviewed.

Only 10 of the 48 test programs reviewed studied dispersion in the presence of ice and only 7 of these varied the ice concentration in the test matrix and only two used Alaskan oil in the testing. Of the 48 studies reviewed, temperature was varied in 15, salinity was varied in 16, and mixing energy was varied in 29.

Most of the unique aspects of chemical dispersant use and effectiveness in the Arctic are due to the potential presence of ice in various forms and concentrations throughout the year. Mixing energy in the arctic environment may be reduced or eliminated due to the presence of ice. Melting ice may result in reduced surface water salinity. Ice may dampen overall surface water mixing or add localized mixing energy to the system. Water temperature is another important factor as cold water temperatures will reduce the dispersant and oil temperature, increase the oil viscosity and potentially reduce the effectiveness of dispersants due to the increased viscosity that may inhibit both the mixing of the dispersant into the oil and the breakup of the oil into small droplets. The impact on dispersant effectiveness of these factors is discussed in more detail in the following sections with specific reference to tests conducted on Alaskan crude oils.

5.4 Oil Type

At the present time the only oils being produced and transported (by pipeline to shore) in the Beaufort and Chukchi Seas are Northstar and Endicott crude oils and are the only crude oils that could be spilled directly into Alaskan offshore waters from present production fields. The Northstar oilfield is located six miles off the Beaufort Sea coast 11 miles northwest of Prudhoe Bay. Oil from this field is shipped to the Trans-Alaska Pipeline System via a trenched 10 inch pipeline to shore. The Endicott field is approximately four miles off the Beaufort Sea coast and 10 miles southeast of Prudhoe Bay. Oil from this field is shipped to the Trans-Alaska Pipeline System via a 16 inch pipeline to shore. No oils are presently being produced in Chukchi Sea waters.

Alaska North Slope Crude (ANS), or Prudhoe Bay crude as it was named in early test programs, has been the Alaskan oil of choice for most of the dispersant effectiveness tests conducted on Alaskan oils. This is evident in Table 5-2 where testing on Alaskan crudes other than the ANS blend crude occurred in only 5 of the research programs reviewed. The ANS or Prudhoe Bay crudes are both oils that were sampled from the Trans-Alaska Pipeline system that delivers Alaskan oil to Valdez. This oil is a blend of the oils produced from the various fields on the North Slope. Because this oil moves to the south by pipeline it is not likely to be spilled in the Beaufort or Chukchi Seas. As shown in Section 1 the physical properties of this Alaskan pipeline blend also have changed over the years and care must be taken when comparing dispersant effectiveness tests conducted on these oils that span many years. Only five of the test programs evaluated dispersant effectiveness on specific North Slope production crudes (Endicott, Northstar and Pt. McIntyre). These oils were used in projects that were conducted for BSEE's predecessor, the Minerals Management Service (MMS), with oils sourced by them specifically for cold water dispersant effectiveness testing. These oils are possibly more representative of the type of crude that might be spilled in the Beaufort and Chukchi Seas. As new oils come into production in the waters of the Beaufort and Chukchi Seas they should be evaluated for their potential for chemical dispersion under the range of environmental conditions they might be spilled in.

5.5 Dispersant Type

Most of the dispersant effectiveness tests on Alaskan oils identified in Table 5-2 used one or both of Corexit 9500 and Corexit 9527 in their testing. This is not surprising since these brands have been the most stockpiled products in North America and have been on the market for many years. Other dispersants tested on ANS crude under a variety of conditions include Archochem D609, Atlantol AT-7, BP 1100WD, Citrikleen, Corexit 9550, Dispersit SPC1000, Dispolene 34S, Dasic Fresh Water, Dasic Slickgone NS, Enersperse 700, Enersoerse 1037, Finasol OSR 5, Finasol OSR 7, Finasol OSR 51, Finasol OSR 52, Inipol IP90, Inipol IPF, Inipol PC, OFC D-609, Slickgone NS, and Superdispersant 25. Many of these products are no longer commercially available or on the US EPA NCP list of approved products for US waters. The significance of dispersant type will be discussed more fully when addressing the other variables that are specific to Arctic dispersant use (cold temperatures, salinity, mixing energy and ice). If new chemical formulations are developed or ‘green’ dispersants are developed their effectiveness on the crude oils currently being produced on the North Slope should be tested using bench and large scale test methods.

5.6 Water Temperature

There is concern in temperate or subarctic climates that temperature, per se, is a problem in dispersant effectiveness, and that dispersants should not or cannot be used in cold climates. This concern is generally unfounded, except in the case of so-called "high pour point oils", some of which can become semi-solid at temperatures well above freezing. Reduced temperature simply increases the viscosity of the dispersant product and the spilled oil. Dispersant products can be formulated to be non-viscous in cold temperatures, so this is not a problem. The viscosity of the spilled oil will become higher at low temperatures, but perhaps not too high for effective chemical dispersion. In early work by Mackay (1979), that used the Mackay Nadeau and Steelman (MNS) test and a hoop tank, it was concluded that the primary effect of water temperature was to lower the oil temperature and increase the oil viscosity which in turn reduced the dispersant effectiveness. In later work where Prudhoe Bay crude oil was used, Mackay (1986) concluded that “There is no inherent reason to suggest that cold climate dispersion is significantly less feasible than temperate dispersion” and that “dispersion is likely to require more dispersant under these cold conditions but the extra amount is unlikely to be large except when the oils are unusually viscous, close to their pour point or waxy”. Tests conducted using the ExxonMobil dispersant effectiveness test (EXDET) by Mackay (1995) found a slight **decrease** in effectiveness of C 9527 on ANS crude as the temperature **increased** from 4.4 °C to 15.5 °C. Byford et al (1983) found in Warren Spring Laboratory tests (WSL) and tank tests, that included North Slope Crude oil conducted at 0 and 10 °C, that in all cases the dispersant performance was not reduced in the lower temperatures and in some cases was enhanced. Moles et al (2001, 2002) found that dispersant effectiveness, as measured by the swirling flask test (SFT), on fresh ANS was below the detectable limits when the water temperature was 3 °C. They also found that the effectiveness of Corexit 9500 was similar at 10 and 22 °C in 32 ppt salt water but lower effectiveness was measured in the cold condition for Corexit 9527. Chandrasekar et al (2005, 2006) found that the best dispersion of ANS was achieved in the baffled flask test (BFT) at 22 °C with a reduction in effectiveness at both 5°C and 35 °C. Fingas et al (2006) found that Corexit 9500 was equally effective in the SFT test on ANS crude at temperatures between 5 to 10 °C and **decreased** when the temperature **increased** to 25 °C. In a study using Alberta Sweet Mixed Blend crude oil and the SFT test Fingas et al (2005b) found a similar trend with similar effectiveness at 5 to 20 °C and a reduction in effectiveness at 25 °C. Earlier work with the SFT test by Fingas et al (1991) found a reduction in dispersant effectiveness when temperatures were lowered from 50 °C to 0 °C. Large scale tests conducted in cold water conditions (-2.8 to 3.3°C) at the Ohmsett facility (SL Ross 2002, 2003, 2006, 2006b) resulted in near complete dispersion (74 to 99%) of fresh ANS, Endicott, Northstar and Pt. McIntyre crude oils. The weathered and emulsified oils were not as easily dispersed in a number of the tests with measured effectiveness ranging from 3 to 35%.

Crude oils that are relatively non-viscous and whose viscosities do not increase to very high values when temperatures are lowered to 0° C are likely to be chemically dispersible over the full range of possible water temperatures. On the other hand, fresh or weathered oils that are relatively viscous to begin with, but yet dispersible at high temperatures, may become excessively viscous and un-dispersible when lowered to freezing temperatures. The main lesson here is that it is the viscosity of the oil at the water temperature in which it is spilled that is the key factor in deciding dispersant effectiveness and not the temperature per se. This points to the need to fully understand the fresh and weathered oil viscosities of the specific oils that are likely to spilled in cold waters. This is accomplished through laboratory testing and modelling. Once such analysis is done, it should become evident if a specific oil is a good candidate for dispersant use or not. From the past testing that has been conducted on Alaskan oils it appears that the Alaskan oils produced to date are generally dispersible at cold temperatures when fresh and slightly weathered but may not be readily dispersed when heavily weathered and emulsified. Additional cold water testing of the chemical dispersibility of specific Alaskan oils when weathered and emulsified may be useful to further define the time window of opportunity for the successful dispersion of these oils under typical conditions that could be encountered in the study region.

5.7 Water Salinity

An extensive review of worldwide scientific and technical journals was undertaken for the US Department of Interior (SL Ross 2010) to identify relevant literature on the use of chemical treating agents for oil spill response in fresh and brackish water. This review found that numerous laboratory-scale, meso-scale and field studies, dating back to the late seventies, have been conducted to study the effect of water salinity on the effectiveness of oil spill chemical dispersants on a range of oils. The consistent significant finding of all of these tests is that dispersant designed for use in marine environments (30 to 35 ppt salinity) are considerably less effective when the salinity falls below about 20 ppt or above 40 ppt. Of the dispersants most commonly used in US waters, Corexit 9500 has been shown to be more effective than Corexit 9527 in lower salinity waters.

Dispersants have been formulated for use in fresh water and these have also been tested for effectiveness over a range of water salinities, although not as extensively as the marine dispersants. The effectiveness of the freshwater dispersants have been shown to generally be much better than the marine products in freshwater but often achieve their best results in waters between 10 and 20 ppt salinity.

Most of the research identified in Table 5-2 where salinity was varied in the test matrix form part of the previous review described above (SL Ross 2010). Table 5-2 references identify research that was specific to Alaskan crude oils (exclusively Alaska North Slope blend or Prudhoe Bay crude). The effectiveness of dispersants on the Alaskan oil under varying water salinities generally is consistent with the findings for other crude oils. The work by Chandrasekar et al (2006) and Nagaraja et al (2008) were not part of the 2010 review. It is interesting to note that in the work reported by Chandrasekar and Nagaraja that the effectiveness of dispersant A (assumed to be Corexit 9500 based on previous reports by this author) on ANS crude in the BFT varied by less than 15% over the salinity range (from 10 to 34 ppt) and temperature range tested (5 to 35 °C). These tests showed greater effectiveness of a marine dispersant (Corexit 9500) on ANS crude at low water salinity than has been demonstrated by many other test programs. This improvement may be due to the higher energy level imparted in the BFT when compared to the SFT which was used in many of the other tests that investigated the dispersibility of ANS crude at different temperatures and salinities. The work conducted by Abbasova (2005) also show high dispersibility of a Caspian crude oil in low salinity water (12ppt) using the BFT. In early work by Cox and Shultz (1981) using the MNS test apparatus, no difference in dispersant effectiveness was identified over salinities ranging from 10 to 32 ppt. Unfortunately the dispersants used in these tests were not identified by brand name.

The water salinities in the US Beaufort and Chukchi Seas are generally greater than 20 ppt, even during the spring ice melt season, with the exception of fresh water outflows inside the barrier islands of the US Beaufort Sea and isolated near shore regions of the Chukchi Sea (see Task 1 Report). Additional testing of Alaskan oils in low salinity water may be a low priority since chemical dispersants designed for marine use have been shown to generally be effective on most oils and specifically on ANS crude oil in waters with salinities 20 ppt and greater. If new 'green dispersants' are developed and proposed for Arctic use their effectiveness in water salinities ranging from 15 to 35 ppt should be evaluated on Alaskan oils.

5.8 Mixing Energy

Mixing energy is of obvious importance to the dispersion of marine oil spills: simply put, the more mixing the better. Oil slicks can be broken up into small droplets and disperse naturally under high energy conditions but much more rapid dispersion and dispersion under much less vigorous wave energies can be accomplished by applying chemical dispersants as described in Section 2 above. The bench-scale, and meso-scale laboratory tests and outdoor wave tanks all impart a slightly different mixing energy to the oil-water-dispersant system and thus can result in different dispersant effectiveness estimates for a given oil and dispersant combination. A comparison of dispersant effectiveness estimates using identical oils and dispersants was made for the swirling flask test (SFT), baffled flask test (BFT), ExxonMobil dispersant effectiveness test (EXDET), the Warren Spring Laboratory test (WSL), and Ohmsett test tank (SL Ross 2011).

Based on the results of this study it can be assumed that the mixing energy rankings for these tests fall into the following pattern: SFT<BFT<EXDET<Ohmsett. Clark et al (2005) found a similar relationship in their comparison of small-scale DE test results: SFT< EXDET <BFT=WSL. Numerous other studies have compared small scale test results from different test apparatus and have directly measured the energy present in the various test apparatus. The issue of wave energy and dispersant effectiveness is universal to both warm and cold climate conditions and a complete discussion of this issue is beyond the scope of this review. The issue is mentioned only to highlight the fact that results from one set of tests using one apparatus and test method may not give the same results or trends as those from another method. This may be one of the reasons for the somewhat inconsistent results that have been reported for dispersant effectiveness as a function of temperature and salinity discussed above. Of more importance to this document is the effect that the presence of ice has on the level of energy available for the chemical dispersion of oil. The attenuation of waves and surface energy by floating ice is a well-known phenomenon and the higher the ice concentration the more the waves are dampened. The influence of ice on the dispersion process is discussed under a separate heading below.

5.9 Effect of Ice on Dispersant Effectiveness

There have been a limited number of dispersant effectiveness studies where ice has been present during the test and even fewer where Alaskan oils have been tested. Dispersant effectiveness in ice was studied by Mackay et al. 1979; Cox and Shultz 1981; Byford et al. 1983; Brown et al. 1985; and Brown and Goodman 1996, SL Ross 2002, Owens 2004, Spring et al 2006, Sorstrom et al 2010. The work here ranged from experiments in small containers, to medium sized-tank experiments, to experiments at a large wave basin in Calgary, at the Ohmsett facility and in one field trial. Of these studies only those by Owens and SL Ross used Alaskan oils.

In the small-scale tests conducted by Cox and Shultz and Byford the presence of ice with a surface coverage of between 20 and 50% generally increased the chemical dispersion of the oil. This was speculated to be due to the result of the pumping action of the broken ice pieces. Brown et al 1985 also measured higher dispersion rates than achieved in similar open water conditions in tests where both slush and broken ice were present. Tests in the Ohmsett facility (SL Ross 2002) with fresh and weathered (10% evaporative loss) ANS crude conducted in 80% ice cover resulted in greater than 95% dispersion. The measured dispersant effectiveness (DE) values for ANS weathered to 20% loss were 54% in 8/10th ice, 30% in 4/10th ice and 22% in open water.

All of these tests were conducted in non-breaking wave, low energy swells. Chemical dispersion was enhanced by the presence of ice in these tests. The increased dispersion over open water conditions was attributed to the pumping action or turbulence caused by the movement of the ice pieces in the swell. Owens et al (2004) reported similar improvement over open water conditions in the chemical dispersion of ANS crude oil when brash ice was present in 4/10 and 8/10 coverage.

The presence of ice has been shown to improve the chemical dispersion of oil in low energy conditions by a number of studies. Successful dispersion of fresh and evaporated ANS in ice appears to be possible in lower wave energies than would normally disperse oil in open water conditions due to the additional turbulence caused by the moving ice. Some movement of the broken ice is necessary to generate the dispersion.

Ship propeller wash and water jets have been shown to be effective in dispersing oil that has been treated with dispersant in a broken ice system in the absence of any natural mixing. This was demonstrated in meso-scale tests and in a wave basin (Nedwed et al 2007, Spring et al 2006) and in the field (Sorstrom et al 2010). Oil treated by dispersant in a solid or 80+% ice cover was effectively dispersed in all of these tests using ice-breaking, ship propeller wash and water jets. In all cases the droplet sizes generated were very small and the droplets remained suspended in the water for long periods.

Table 5-2 Chemical Dispersant Research on Alaskan Oil: Summary Table

Research Paper	Oil	Dispersant	Test Method[1]	Parameters Varied in Tests[2]			
				Temp	Salinity	Energy	Ice
Abbasova, A. et al. 2005	Chirag crude oil (Caspian Sea)	Finasol OSR51, Superdispersant 25, Corexit EC 9527a, Corexit EC 9500a, Slickgone NS, Inipol IP90	BF	X	X	X	O
Anderson, J.W., D.L. McQuerry, S.L. Kiesser. 1985.	Alaska North Slope	14 dispersants	MNS	X	X	X	O
Belore, R. 2003.	fresh and weathered Hibernia and ANS crude oils	Corexit 9500 and 9527	Ohmsett wave tank	X	X	X	O
Belore, R., S. Ross. 2000	Alaskan North Slope crude	Corexit 9500 and 9527	SLR wave tank	X	X	X	O
Blondina, G., M Singer, I. Lee, M. Ouano, M. Hodgins, R. Tjeerdema. 1999.	Prudhoe bay crude plus various others	9500 & 9527	SF	X	√	X	O
Brandvik, P.J., 0.0. Knudsen, M.O. Moldestad and P.S. Dating, 1995.	Norwegian Oils Only	Inipol IPF, Inipol PC, Enersperse 700, Finasol OSR-52, Dasic Fresh Water, 9500 & 9527 + others	IFP	X	√	X	O
Brown, H.M., D.K.Weiss, R.H. Goodman. 1990	North Slope & Drift River crude	Corexit 9550 or 9527	Esso Wave Tank	X	X	X	O
Brown et al. 1985	Federated crude (ASMB)	Corexit 9527 & CRX-8	Esso Wave Tank	X	X	X	X

Research Paper	Oil	Dispersant	Test Method[1]	Parameters Varied in Tests[2]			
				Temp	Salinity	Energy	Ice
Brown, H.M., R.H. Goodman. 1987	ANS	9527, 9550, Enersperse 700	Esso Wave Tank	X	X	√	O
Brown and Goodman 1996.	Federated crude (ASMB)	Corexit 9500 and Corexit 9527	Esso Wave Tank	X	X	√	√
Byford, D., P. Green, A. Lewis. 1983	Lago Medio, North Slope Crude, Medium Fuel Oil	Corexit 9527, Corexit 9550 BP1100WD, Fiansol OSR5, Dispolene 34S, Arcochem D609	WSL, BP Wave Tank	√	√	X	X
Chandrasekar, S. G.A., Sorial, J.W. Weaver. 2003.	Prudhoe Bay South Louisiana crude and #2 Fuel oil	Corexit 9500 and Dispersit-SPC 1000	BF	√	X	√	O
Chandrasekar, S.; Sorial, G.A.; Weaver, J.W. 2006.	Alaskan Prudhoe Bay, South Louisiana crude oil, No. 2 Fuel Oil (fresh & weathered)	Corexit 9500 and Dispersit-SPC 1000	BF	√	√	√	O
Cox, J., L. Shultz 1981	Sadlerochit crude fresh, 10 and 30% weatehred, 10% weathered Arctic diesel, 10% weathered Kuparuk crude	X, Y, Z	MNS, Hoop Tank	X	X	√	√
Fingas, M., B. Fieldhouse, Z. Wang. 2006.	ANS	Corexit 9500 and 9527	SF	√	√	X	O
Fingas, M., B.Fieldhouse, Z.Wang. 2005b	ASMB	Corexit 9500	SF	√	√	X	O

Research Paper	Oil	Dispersant	Test Method[1]	Parameters Varied in Tests[2]			
				Temp	Salinity	Energy	Ice
Fingas, M., L. Ka'aihue. 2005a	Various including ANS	various	various	√	√	√	O
Fingas, M.F., I. Bier, M. Bobra and S. Callaghan. 1991	ASMB, Norman Wells, Adgo	Corexit 9527, Enersperse 700 and Citrikleen	SF	√	√	X	O
Fiocco, R.J., P.S. Daling, G. DeMarco, R.R. Lessard, 1999.	Alaska North Slope	Corexit 9500	MNS, WSL	X	X	√	O
George-Ares, A., R.R. Lessard, K.W. Becker, G.P. Canevari and R.J. Fiocco,	ANS + 3 other non-Alaskan oils	Corexit 9500, calcium chloride modified 9500, Dasic freshwater, Enersperse 1037, Inipol IPF	EXDET	X	√	X	O
Lewis, A.; Crosbie, A.; Davies, L.; Lunel, T. 1998.	Forties Blend, Alaskan North Slope crude, and IFO-180 fuel oil	Corexit 9500 and Dasic Slickgone NS	Field test	X	X	√	O
Li, Z., K. Lee, T. King, M. Boufadel, A. Venosa. 2009.	ANS and Mesa crude	Corexit 9500 & Dispersit-SPC 1000	EPA / DFO wave tank	X	X	√	O
Mackay, D. , R. Mascarenhas, K. Hossain, T. McGee. 1979	Alberta Mixed Blend (ASMB), Lago Medio	9527	MNS, Hoop, CSSA	√	X	√	X
Mackay, D. 1995.	Alaskan North Slope crude	Corexit 9527	MNS, WSL, Exdet,Esso Wave Tank	√	√	√	O
Mackay, D., Chau, Y. Poon. 1986	Prudhoe Bay Crude and various others	9527, 9550, BPMA700	MNS, Hoop, RF,Bobra	√	√	√	O

Research Paper	Oil	Dispersant	Test Method[1]	Parameters Varied in Tests[2]			
				Temp	Salinity	Energy	Ice
McAuliffe, C.D. et al. 1981.	Alaskan Prudhoe Bay crude oil	Code Named H & J	Field	X	X	√	O
Moles, A., L. Holland, J. Short. 2002	ANS	9500 & 9527	SF	√	√	X	O
Moles, A.L. Holland, J. Short, 2001	ANS	9500 & 9527	SF	√	√	X	O
Nagarajan, K., N. Deshpande, G. Sorial, J. Weaver. 2008.	Alaskan Prudhoe Bay, South Louisiana crude oil, No. 2 Fuel Oil (fresh & weathered)	Corexit 9500 (A) & Dispersit-SPC 1000 (B)	BF	√	√	√	O
Nedwed, T. , R. Belore, W. Spring, D. Blanchet. 2007	Chayvo Z6	Corexit 9527	SL Ross Wave Tank, AKER Ice Basin (prop wash)	X	X	√	√
Owens, C.K.R. Belore, 2004.	Alaska North Slope, Hibernia, Chayvo	Corexit 9527	Ohmsett	X	X	√	√
Payne, J.R. et al. 1985	Alaskan Prudhoe Bay crude oil	Corexit 9550, Finasol OSR-7, EC. O ATLANT'TOL AT-7, and OFC D-609	Old EPA protocol	√	√	X	O
SL Ross, MAR Inc. 2003	ANS, Endicott, Northstar, Middle Ground Shoal & Pt. McIntyre (fresh and weathered)	Corexit 9527	SLR Wave Tank & Ohmsett	X	X	√	O
SL Ross, MAR Inc. 2006	ANS, Endicott, Northstar & Pt. McIntyre (fresh and weathered)	Corexit 9527	SLR Wave Tank & Ohmsett	X	X	√	O

Research Paper	Oil	Dispersant	Test Method[1]	Parameters Varied in Tests[2]			
				Temp	Salinity	Energy	Ice
SL Ross, MAR Inc. 2009	ANS, Endicott, Oseberg, Rock, Ewing Bank, IFO 30	Corexit 9500	SLR Wave Tank & Ohmsett	X	X	√	O
SL Ross. 2002.	Alaska North Slope and Hibernia (fresh and weathered)	Corexit 9500 & 9527	Ohmsett	X	X	√	√
SL Ross. 2006.	fresh, air sparged and emulsions of Endicott, IFO 30, IFO 120 and Sockeye crude	Corexit 9500 & 9527	SLR Wave Tank & Ohmsett	X	X	√	O
SL Ross. 2010. (lit review)	Various including ANS	various	various	X	√	X	O
SL Ross. 2011	Endicott, ANS plus 12 other crude oils	Corexit 9500	Ohmsett, WSL, BF,SF,Exdet	X	X	√	O
Smith, D., G. Holliday. 1979	ANS	H & J	Field tests	X	X	√	O
Spring, W, T. Nedwed, R. Belore.2006	Chayvo Z6	Corexit 9527	SL Ross wave tank & AKER wave basin (prop wash)	X	X	√	√
Sorial, G.A.K.M. Karen, H. Edith, A.D. Venosa, D.W. King. 2001.	Alaskan Prudhoe Bay and South Louisiana crude	18 Different Products	SFT & BF	X	X	√	O
Sørstrøm, S.E., Per Johan Brandvik, I. Buist, P. Daling, D. Dickins, L. Faksness, S.Potter, J. Rasmussen and I. Singsaas.2010.	Troll B crude	Corexit 9500	Field test	X	X	√	√

Research Paper	Oil	Dispersant	Test Method[1]	Parameters Varied in Tests[2]			
				Temp	Salinity	Energy	Ice
Strom-Kristiansen, T., P.S. Daling, A. Lewis, A.B. Nordvik. 1994.	ANS plus Brent Blend, Murban and Bonny Light	9527, 9554, Enersperse 700,Several others	MNS, IFP, WSL	X	X	√	O
Venosa, A.D.G.A. Sorial, D.W. King. 2001	ANS and South Louisiana Crude	Six – test results not tied to dispersant brand	BFT	X	X	X	O
Venosa, A., K. Lee, M. Boufadel, Z. Li, E. Wickley-Olsen, T. King, 2008	ANS & Mesa light	Corexit 9500 and Dispersit SPC 1000	EPA/DFO wave tank	X	X	√	O
White, D.M.; Ask, I.; Behr-Andres, C. 1999.	Alaska North Slope	Corexit 9500	Modified SFT & EXDET	X	X	√	O
Wrenn, B., A. Virkus, B. Mukherjee, A. Venosa. 2009.	Mars crude	Various experimental formulations	BF	X	X	X	O

[1] RF- Rotating Flask, MNS- Mackay Nadeau Steelman test, Bobra- double tube test, SFT- Swirling Flask, BFT- EPA Baffled Flask Test, IFP- French dilution tests, WSL-Warren Spring Laboratory rotating flask, EXDET- ExxonMobil Dispersant Effectiveness Test

[2] O – parameter not tested, √ parameter varied in test, X parameter not varied.

6 Identification of Knowledge Gaps

The results of the review of past dispersant effectiveness testing on Alaskan oils (section 5) and the environmental conditions in the US Chukchi and Beaufort Seas relevant to chemical dispersion (chapter 4) are discussed in this section with the goal of identifying gaps in our understanding of the potential effectiveness of dispersants in these regions.

6.1 Water temperature

The dispersibility of a crude oil is a strong function of its viscosity, which in turn is often very temperature dependent. The surface water temperatures in the Chukchi and Beaufort Seas in the open water seasons can vary from close to freezing (-2 °C) to upwards of 14 °C with considerable spatial variability in both regions. As crude oils cool their viscosities increase and with increasing viscosities there is a potential for the reduction of dispersant effectiveness. If the water temperature is below the pour point of the oil and the oil is no longer fluid the oil will also not be amenable to chemical dispersion because the dispersant cannot easily mix with the oil. There is really no water temperature that will completely restrict the use of chemical dispersant. The main lesson here is that it is the viscosity of the oil at the water temperature in which it is spilled that is the key factor in deciding dispersant effectiveness and not the temperature per se. The oil viscosity – temperature relationship must be considered for each candidate oil before an evaluation of the potential for dispersant effectiveness can be made. From the past testing that has been conducted on Alaskan oils it appears that the Alaskan oils produced to date are generally dispersible at cold temperatures when fresh and slightly weathered but may not be readily dispersed when heavily weathered and emulsified. Additional cold water testing of the chemical dispersibility of specific Alaskan oils when weathered and emulsified may be useful to further define the time window of opportunity for the successful dispersion of these oils under typical conditions that could be encountered in the study region.

6.2 Water Salinity

Most of the past DE tests on crude oils in general and Alaskan oils specifically have shown that dispersant designed for use in marine environments (30 to 35 ppt salinity) are considerably less effective when the water salinity falls below about 20 ppt or above 40 ppt. However, the effectiveness of a dispersant on both ANS crude and a Caspian crude oil in the baffled flask test (BFT) showed considerably higher dispersibility at low water salinities (10 to 15 ppt) than has been demonstrated in many other test programs. This improvement may be due to the higher energy level imparted in the BFT when compared to the SFT which was used in many of the other tests that investigated the dispersibility of ANS crude at different temperatures and salinities.

With the exception of isolated near shore fresh water outlets there is minimal variation (between 28 and 34 ppt), both temporally and spatially, in surface water salinity throughout the U.S. Chukchi and Beaufort Sea regions. This offshore salinity variation is well within the optimal effectiveness range for marine chemical dispersants.

Water salinities in the nearshore area of the Beaufort Sea can be considerably lower than the offshore areas for short periods of the year due to the influence of fresh water river outflows and ice melt. Fresh water from river outflow can form a 1 to 2 m deep lens under the landfast ice that may extend up to 25 km offshore from the major river mouths. The surface water salinities in these areas approach that of fresh water during the early ice breakup period and prior to the mixing of the upper and lower water layers by strong winds and waves. The presence of this near shore fresh water during this period could hinder the effectiveness of chemical dispersants. Additional work on the effectiveness of dispersants over a range of salinities under realistic breaking wave conditions may be warranted to further investigate their potential for these near shore fresh water outflow regions.

6.3 Presence of Ice

There have been a limited number of dispersant effectiveness studies where ice has been present during the test and even fewer where Alaskan oils have been tested. The presence of ice has been shown to improve the chemical dispersion of oil in low energy conditions. Successful dispersion of fresh and evaporated ANS in ice appears to be possible in lower wave energies than would normally disperse oil in open water conditions due to the additional turbulence caused by the moving ice. Ship propeller wash and water jets have been shown to be effective in dispersing oil that has been treated with dispersant in a solid or 80+% ice cover in the absence of any natural mixing. In these cases the drop sizes generated were very small and the drops remained suspended in the water for long periods.

In the Chukchi Sea region open water periods where conventional aerial application methods could be used generally exist only in the months from June through November. Open water is most common in the months of July through October in this region but the shoulder months of June and November may present dispersant application opportunities depending on the ice year. In the Beaufort Sea region the maximum likely extent for open water dispersant use is from July to October with the more likely season being from August to October. The remainder of the year will see short transition periods from open water to complete (90+ %) ice cover which will affect conventional dispersant use. In ice conditions with less than 3/10ths cover chemical dispersants will perform much the same as in open water conditions since the surface mixing energy is not overly dampened by the presence of the ice. The presence of greater than 9/10ths ice either encapsulates the oil making it impossible to target with aerial applied dispersant or dampens the surface energy such that there is insufficient energy to break the oil into droplets once treated The performance of dispersants in 3/10ths to 8/10ths ice cover without additional mixing energy applied is somewhat uncertain and requires additional study. Additional research on the potential for dispersant use under partial ice cover conditions is currently underway (OGP 2014, BSEE 2014).

6.4 Wave Energy

An assessment of hindcast historical wind data and a correlation between wind speeds and wave energy was used to identify the percentage of time that aerial dispersant operations could be viable in section 5, both from a spray application efficiency standpoint and the presence of sufficient wave energy for oil dispersion. Based on this assessment chemical dispersant use would be favorable for 80 to 90% of the time in the two regions. This does not account for other operational limitations such as visibility and daylight hours as this was out of the scope of the study. Based on this assessment wind speeds and wave heights in the region should not generally be an impediment to chemical dispersant use.

Mixing energy is of obvious importance to the dispersion of marine oil spills with more mixing being better. Oil slicks can be broken up into small droplets and disperse naturally under high energy conditions but much more rapid dispersion and dispersion under much less vigorous wave energies can be accomplished by applying chemical dispersants. The bench-scale, and meso-scale laboratory tests and outdoor wave tanks all impart a slightly different mixing energy to the oil-water-dispersant system and thus can result in different dispersant effectiveness estimates for a given oil, dispersant water salinity, temperature combination. A comparison of dispersant effectiveness estimates for the swirling flask test (SFT), baffled flask test (BFT), ExxonMobil dispersant effectiveness test (EXDET), the Warren Spring Laboratory test (WSL), and Ohmsett test tank ranks the energy for these tests into the following pattern: SFT<BFT=WSL<EXDET<Ohmsett. The issue is mentioned only to highlight the fact that results from one set of tests using one apparatus and test method may not give the same results or trends as those from another method. This may be one of the reasons for the somewhat inconsistent results that have been reported for dispersant effectiveness as a function of temperature and salinity discussed above. It is always preferable to test dispersants under the most realistic conditions possible but this is not always possible due to permitting requirements for field trials or costs associated with large tank tests. Additional DE testing on Alaskan oils using realistic breaking wave conditions and varying environmental conditions would be useful to solidify our understanding of the potential for chemical dispersants.

6.5 Alaskan Oil Types

At the present time the only oils being produced and transported (by pipeline to shore) in the Beaufort and Chukchi Seas are Northstar and Endicott crude oils and are the only crude oils that could be spilled directly into Alaskan offshore waters from present production fields. No oils are presently being produced in Chukchi Sea waters. Alaska North Slope Crude (ANS), or Prudhoe Bay crude as it was named in early test programs, has been the Alaskan oil of choice for most of the dispersant effectiveness tests conducted on Alaskan oils. Only five of the test programs evaluated dispersant effectiveness on specific North Slope production crudes (Endicott, Northstar and Pt. McIntyre). These oils were used in projects that were conducted for MMS with oils sourced by them specifically for cold water dispersant effectiveness testing. These oils are possibly more representative of the type of crude that might be spilled in the Beaufort and Chukchi Seas. As new oils come into production in the waters of the Beaufort and Chukchi Seas they should be evaluated for their potential for chemical dispersion under the range of environmental conditions they might be spilled in.

6.6 Dispersant Types Tested

Most of the dispersant effectiveness tests on Alaskan oils identified in Table 5-2 used one or both of Corexit 9500 and Corexit 9527 in their testing. This is not surprising since these brands have been the most stockpiled products in North America and have been on the market for many years. More wide spread testing of additional National Contingency Plan Listed dispersants on Alaskan oils under realistic conditions would provide spill responders with important information concerning the potential use of other products in this environment.

7 Meso-Scale Tank Tests

After discussion with the a technical representative from BSEE, a suite of DE tests using the SL Ross wind-wave tank on four Alaskan crude oils with four water salinities were selected for additional study to shed more light on the effectiveness of marine dispersants over a range of water salinities under high energy breaking wave conditions.

7.1 Oils and Dispersant Used in Test Program

Four Alaskan crude oils were used in the test program. The oils and their basic fresh and weathered oil physical properties are shown in Table 7-1. The second column in Table 7-1 shows the degree of weathering that each of the oils received to achieve the weathered oil properties shown. The densities and viscosities reported in Table 7-1 were measured by SL Ross during the course of the current project. The modeling constants used to estimate volume percent evaporation as a function of oil density shown in the last four columns of the table are from previous oil analyses conducted on the test oils (SL Ross, MAR, DF Dickins, 2008).

Table 7-1 Test Oil Properties

Oil Name	Degree of Weathering (% loss by mass)	Density (kg/m^3 @ 10 °C)		Viscosity (cP @ 10 °C & 100 s^{-1})			Evaporation Modeling Constants			
		Fresh	Weathered	Fresh	Weathered	Weathered & Emulsified (50% water content)	Standard density (kg/m^3)	Standard density temperature (°C)	Density Constant #1	Density Constant #2
Endicott	6.0	0.924	0.935	340	1030	2370 to 3380	920.8	288.7	59.0	0.7736
Kuparuk	13.1	0.923	0.951	124	970	2050 to 4400	920.5	288.7	169.9	0.585
Northstar	43.1	0.823	0.869	1	20	not applicable	820.7	288.7	104.3	0.804
ANS Blend	21.4	0.879	0.940	19	1230	4000 to 5000	869.3	288.7	163.2	0.635

7.2 Test Methods and Equipment

All tests were conducted in the SL Ross wave tank shown in Figure 7-1. This tank is 10 m long by 1.3 m wide by 1.2 m deep and is fitted with a computer controlled wave paddle and energy dissipating beach. The tank is fitted with a cooling coil that permits the maintenance of the water at temperatures down to near freezing conditions. The tank was operated with a 20 cm breaking wave (trough to crest) that was programmed to break in the oil slick every 30 seconds. Tests were run for 15 minutes. Oil was held within the wave breaking zone using an air bubble barrier. Dispersant effectiveness was quantified by collecting the surface oil remaining at the end of each test to determine the percentage of oil dispersed and by measuring the dispersed oil drop size distributions using a LISST particle size analyzer placed 40 cm below the water surface in the center of the bubble barrier containment zone.

Figure 7-1 SL Ross Wave Tank

For the fresh and weathered oil tests approximately 750 ml of oil was placed into a container, weighed, emptied onto the water surface inside the containment area and the empty container re-weighed to determine the mass of oil discharged. Dispersant was applied using an air pressure powered sprayer fitted with a Spraying Systems Company flat fan nozzle (800015) operated at 50 psi. The dispersant sprayer is shown in Figure 7-2. The quantity of dispersant needed to achieve a 1:20 dose rate (by mass) was loaded into the sprayer prior to application and the full quantity of dispersant was applied to the surface of the oil. This dose rate was used as it is the manufacturer's recommended dosage for general use. The dose rate was not changed in the study so comparisons of dispersant effectiveness with varying water salinities could be made with all other conditions kept constant. For the weathered and emulsified oil tests 500 ml of weathered oil was mixed with 500 ml of salt water of the same salinity as the water of the test being conducted. The oil and water were mixed for 8 minutes using the paint stirrer shown in Figure 7-3. This method for realistic emulsion generation was developed in a previous study for the US Department of the Interior (SL Ross 2005). The dispersant dose used in the emulsion tests was again 1:20 based on the total mass of the oil and water mixture spilled.

Figure 7-2 Dispersant Applicator

Figure 7-3 Emulsion Mixer

7.3 Test Variables and Test Matrix

Corexit 9500 was used in all tests. To keep the test matrix at a manageable level only one dispersant to oil ratio was investigated for each type/weathered state of oil. A 1:20 DOR was used in all tests so a comparison of dispersant effectiveness as a function of water salinity could be made.

Alaska North Slope crude (provided by BSEE), Endicott, Northstar and Kuparuk crude oil (from SL Ross supply) were used in the testing. Tests were conducted on fresh, evaporated and evaporated plus emulsified crude oils (3 weathered states in total). Northstar does not form a stable emulsion so tests could not be conducted on emulsions of this oil. Emulsions were generated using the experience and techniques developed during earlier projects funded by the US Mineral Management Service that identified realistic water-in-oil emulsion making methods (SL Ross & A. Lewis, 2005). Tests were conducted in water with salinities of 5, 10, 20 and 30 ppt. All tests were conducted with a water temperature of 10 °C.

7.4 Results

7.4.1 Dispersant Effectiveness (DE) Estimates

The oil collected from within the containment zone at the end of each 15 minute SL Ross wave tank test was treated with a small amount of emulsion breaker (Alcopol) and placed in a heated bath for several hours to facilitate removal of any water. The density of the oil was then measured to allow the estimation of oil loss through evaporation using the modeling constants provided in Table 7-1. This was important for the fresh oils and the lighter Northstar crude in particular. After accounting for evaporative losses the percent of oil lost to the water column, or a raw estimate of percent dispersed, without any adjustment for oil drop size, was calculated for each test. The dispersant effectiveness estimates presented in this section do not take into account the quality of the dispersion as measured by the oil drop size distribution in the dispersion. The results for the unadjusted dispersant effectiveness (DE_{raw}) estimates are presented in Figure 7-4 (Endicott), Figure 7-5 (Kuparuk), Figure 7-6 (Northstar) and Figure 7-7 (ANS). The DE_{raw} values reported in these figures reflect the oil lost from the surface of the containment area over the duration of the test. The complicated beaches in this test tank make it impractical to collect any oil that resurfaces outside of the containment zone at the end of the test. It is likely that some portion of the oil entrained by breaking waves during the test is in the form of large droplets that escape the bubble barrier system at depth, are only temporarily dispersed or entrained and then rise to the surface outside of the containment zone. This will not occur in all tests and the extent of this will be a direct function of the dispersed oil drop size distributions and depth of the dispersions generated. The DE_{raw} values reported in this section reflect the maximum possible DE that can be expected for the oil and water salinity combinations tested. A second dispersant effectiveness that accounts for the oil drop size distribution measured, and is a more realistic indication of dispersant effectiveness in an offshore setting, is presented in the following section.

No tests were completed with fresh water (zero water salinity). The DE values plotted for the zero water salinity values on these figures are the 'no dispersant applied' control test results for the oils. These control results are plotted to enable a rapid comparison of the untreated natural dispersion case to the dispersant applied tests over the range of salinities tested (5 to 30 ppt).

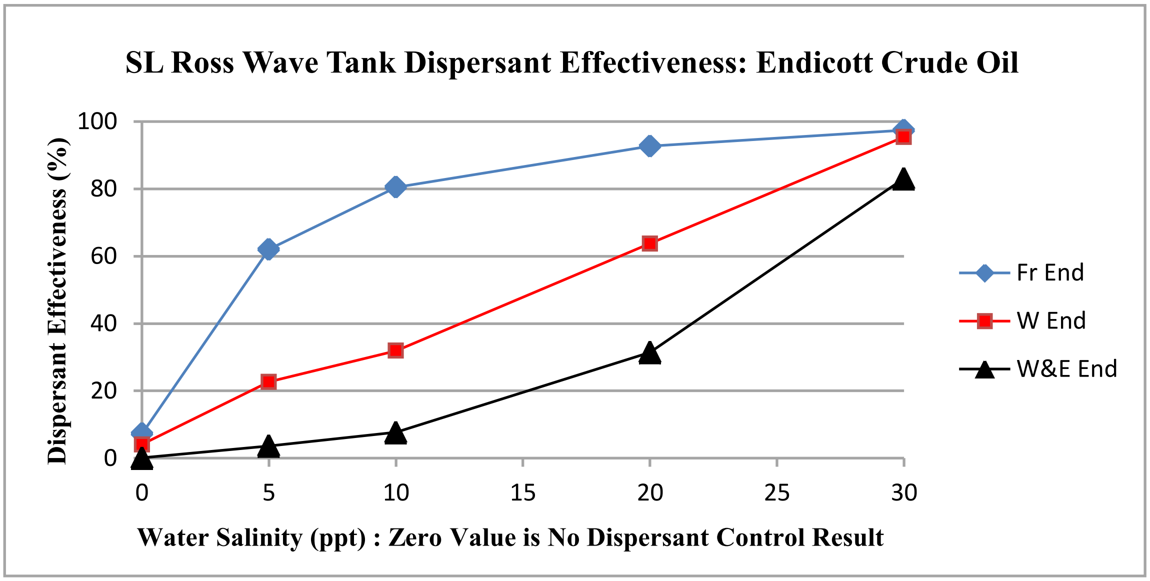


Figure 7-4 Dispersant Effectiveness versus Water Salinity: Endicott Crude Oil

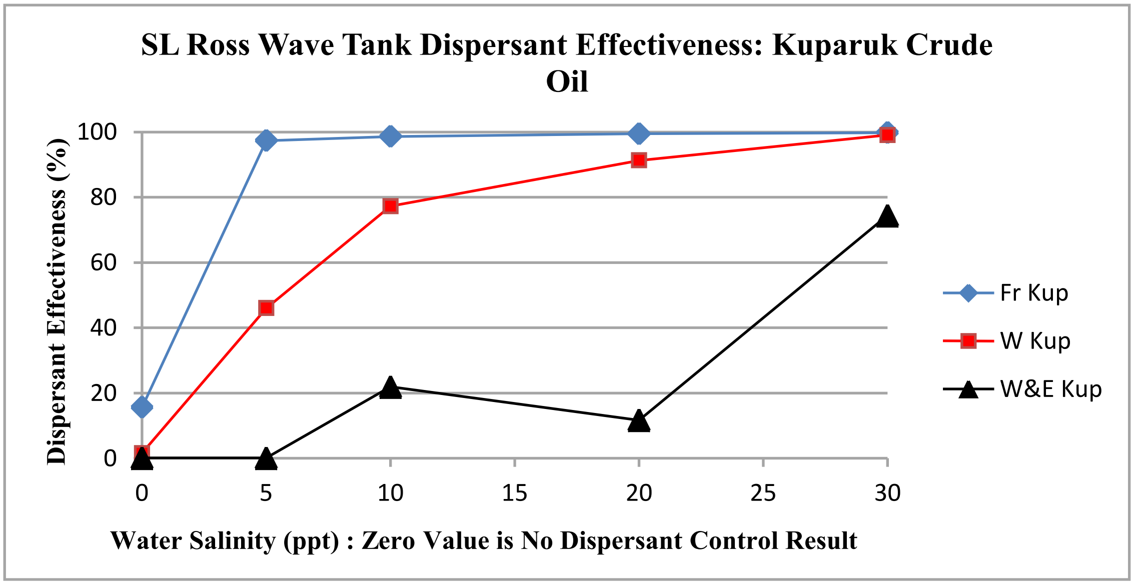


Figure 7-5 Dispersant Effectiveness versus Water Salinity: Kuparuk Crude Oil

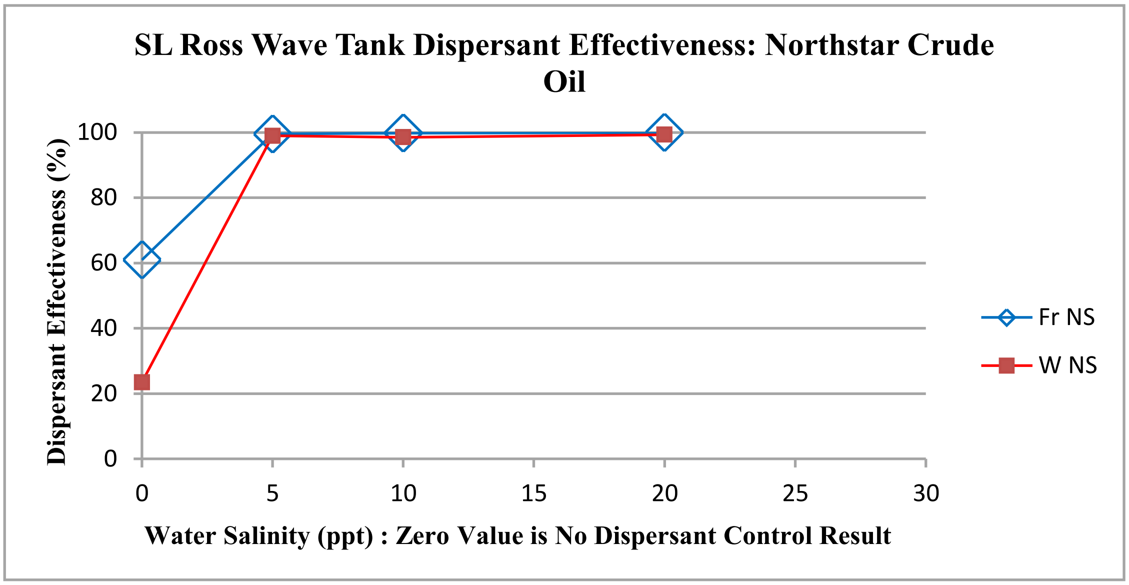


Figure 7-6 Dispersant Effectiveness versus Water Salinity: Northstar Crude Oil

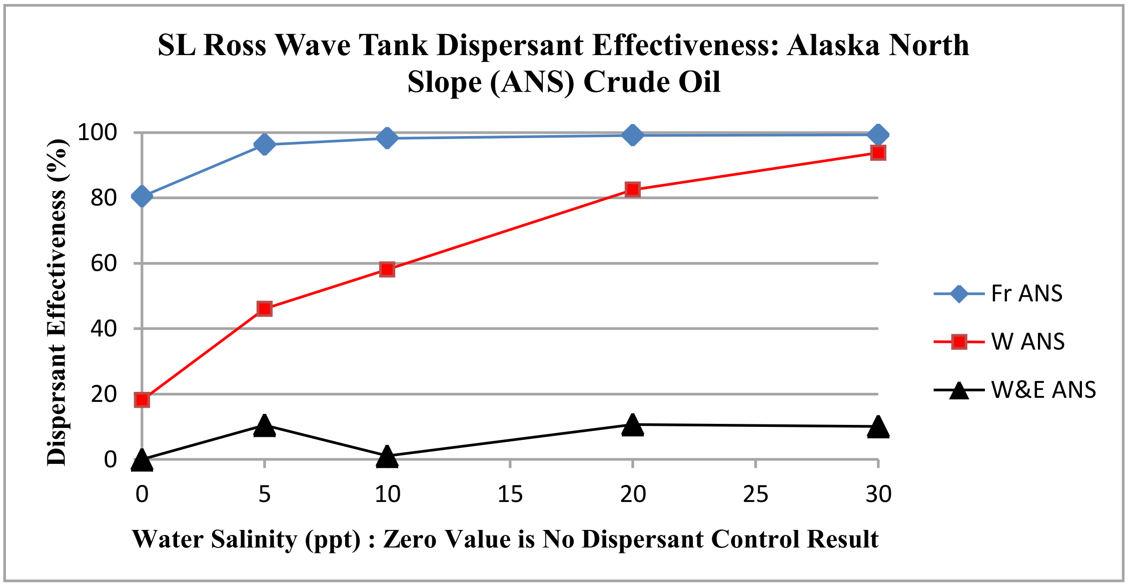


Figure 7-7 Dispersant Effectiveness versus Water Salinity: Alaska North Slope Crude Oil

The DE_{raw} values measured for the various oils tested showed consistent results. The fresh oils were more effectively dispersed than the weathered oils that were more effectively dispersed than the weathered and emulsified oils. The fresh and weathered Northstar crude oils were both completely dispersed at all water salinities (see Figure 7-6). With the exception of the Endicott crude oil, which has the highest fresh oil viscosity of those tested, the fresh oils registered high DE_{raw} (greater than 80%) at all water salinities tested. However, it is important to emphasize that the quality of the dispersions, as measured by the oil drop size distributions, generated varied over the range of water salinities tested and this issue is discussed in the next section. For three of the weathered oils the effectiveness of the dispersant increased as the water salinity increased. Significant dispersion (greater than 60%) of emulsified oil was achieved only for the highest water salinity (30 ppt) tests for the Endicott (Figure 7-4) and Kuparuk (Figure 7-5) oils. The emulsified ANS (Figure 7-7) did not disperse at any of the water salinities tested. Northstar crude did not form a stable water-in-oil emulsion.

About 80% of the fresh ANS (Figure 7-7) was lost to the water column in the control test (no dispersant applied); more than even the much lighter Northstar crude (Figure 7-6) where 60% was lost in the control test. The oil-water interfacial tension (o-w IFT) of the fresh ANS was measured to determine if the oil possibly contains production chemicals that might be affecting the dispersion process. Chemicals are routinely added to crude oil streams during the production process and pipeline transportation to minimize emulsion formation, break water-in-oil emulsions and to improve the flow properties of the crude oil. The o-w IFT of the fresh ANS was measured to be approximately 13 dynes/cm^2. This is considerably lower than the o-w IFTs of the other Alaskan oils tested in this study which were 19.6 dynes/cm^2 for Kuparuk, 22.1 for Northstar and 27 for Endicott, and may explain the high natural dispersion of this oil when fresh. The less dense and much less viscous Northstar crude used in the testing has an o-w IFT of 22 dynes/cm^2. One would normally expect the less viscous Northstar crude oil to have a higher natural dispersion than the more viscous ANS but the natural dispersion for this oil was less than the ANS. This lower natural dispersion of the Northstar crude relative to the ANS can be attributed to Northstar's higher o-w IFT.

7.4.2 Dispersed Oil Drop Size Distributions

A LISST (Laser In-Situ Scattering and Transmissometry) device was deployed at 40 cm below the water surface during all of the tank tests. Figure 7-8 through Figure 7-15 show the results from these measurements. Two figures are provided for each of the test oils. All of the graphs show averaged data during elevated oil concentrations over the full test run. Only those data points where the oil concentration in the water column was 1.5 times the background oil concentration measured in the tank prior to the test are used in generating these averages. This ensures that only data during elevated oil concentrations are used in the analysis. The first figure in each set shows the average volume median diameter (VMD) of the oil drop size distributions. The second figure shows the average volume percent of the oil present in the water column in drops smaller than 70 microns in diameter. This value has been chosen because past research has shown that only oil in drops 70 microns and smaller are likely to remain dispersed in an ocean setting and those greater than 70 microns are likely to be temporarily entrained (Lunel, 1993). This study is the only comprehensive data set that we are aware of that documents the oil drop size distributions for chemically dispersed crude oils in an ocean setting.

The LISST device used in the testing can measure oil drops in the 5 to 500 micron range. Drops larger than this are not registered by the device. If a significant amount of oil is present in the water in drops larger than 500 microns then the oil drop distributions and oil concentrations measured by the LISST are not accurate. During each test the dispersed oil cloud was observed through the viewing window of the test tank and those tests where large oil drops were present (0.5 mm and larger) were identified. **Solid lines** and **enlarged data markers** in the following graphs denote where **reliable LISST data** was recorded, **dashed lines** indicate that the LISST data are **not reliable** due to the presence of large oil drops in the dispersion.

The dispersant effectiveness results presented in section 7.4.1 provide an indication of the percentage of oil removed from the water surface in the oil containment zone by breaking waves in the SL Ross dispersant effectiveness test tank. The results in this section provide additional information on the quality of the oil dispersions through the drop size distribution data. As discussed above it has been shown that drops greater than 70 microns may only be temporarily entrained in certain ocean conditions so it is important to characterize the oil drop size distributions in the dispersions to determine how much of the dispersed oil is likely to remain dispersed. In Figure 7-8 and Figure 7-9 the oil drop size distributions for the fresh Endicott dispersions were reliable for all but the control (no dispersant applied) test. The oil VMD decreased linearly from about 190 microns at 5 ppt to about 110 microns at 30 ppt (Figure 7-8). The volume of drops with diameters less than 70 microns increased in a linear fashion from about 20 % at 5 ppt to 40 % at 30 ppt as seen in Figure 7-9. The LISST data for the weathered and weathered & emulsified tests with Endicott were valid only for the 30 ppt water tests. The trends in drop sizes from fresh to weathered to weathered & emulsified (W&E) oil are as would be expected. The fresh oil test had a smaller VMD and higher percentage of oil in drops less than 70 microns than were present in the weathered oil test and the weathered oil test had smaller drops and a higher percentage less than 70 microns than the W&E test. The oil drops in the Endicott fresh oil dispersion in 30 ppt salt water were the largest of the four fresh oils tested. How the drop size distributions reported in this section affect the estimates of ultimate dispersant effectiveness is presented in the following section 7.4.3.

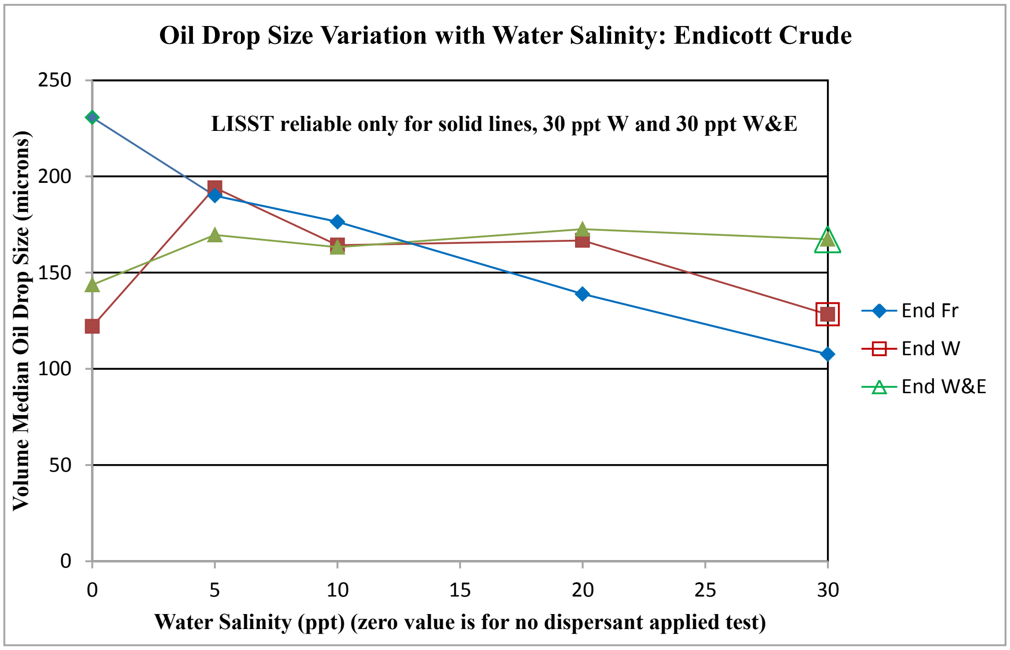


Figure 7-8 Oil Drop Size Variation Versus Water Salinity: Endicott Crude

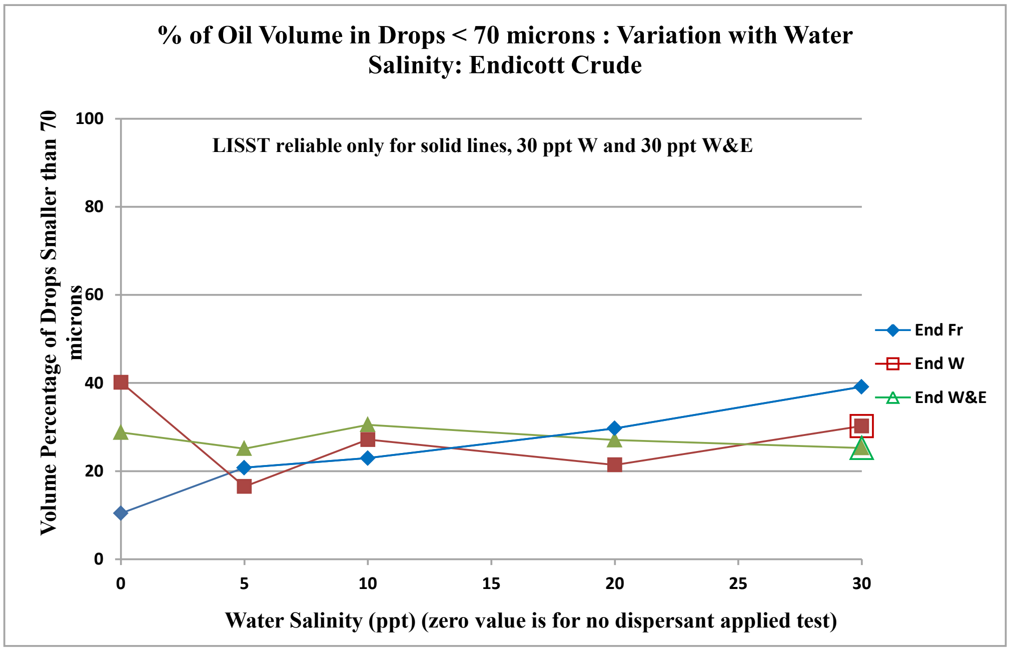


Figure 7-9 Volume Percent of Oil in Drops Less than 70 Microns: Endicott Crude

The LISST results for Kuparuk oil are summarized in Figure 7-10 and Figure 7-11. For both fresh and weathered Kuparuk crude the LISST data are reliable for both the 20 and 30 ppt water salinity tests. The oil drop VMDs for both the fresh and weathered Kuparuk were smaller than 70 microns for the 30 ppt salinity water as seen in Figure 7-10 and a high percentage of oil was present in oil drops less than 70 microns in both cases (85% for the fresh oil and 68% for weathered oil, as seen in Figure 7-11). The VMD oil drop sizes were about 125 microns for both the fresh and weathered oil in the 20 ppt salinity water tests, considerably larger than in the 30 ppt tests (Figure 7-10). The W&E dispersion in 30 ppt salt water had a VMD of about 180 microns, and only about 25% of the dispersed oil was in drops less than 70 microns.

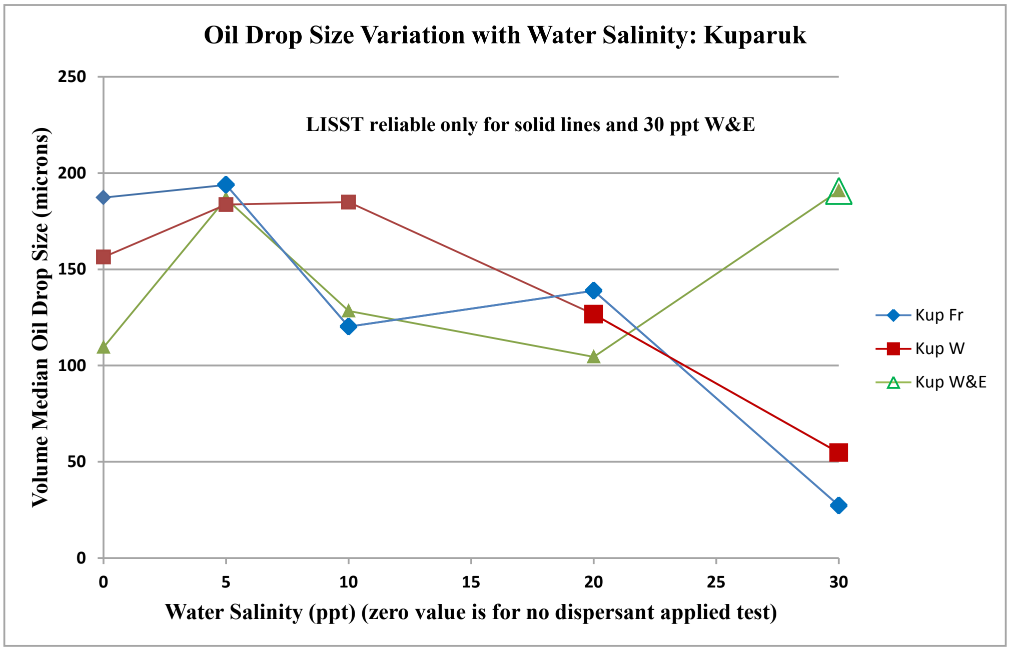


Figure 7-10 Oil Drop Size Variation Versus Water Salinity: Kuparuk Crude

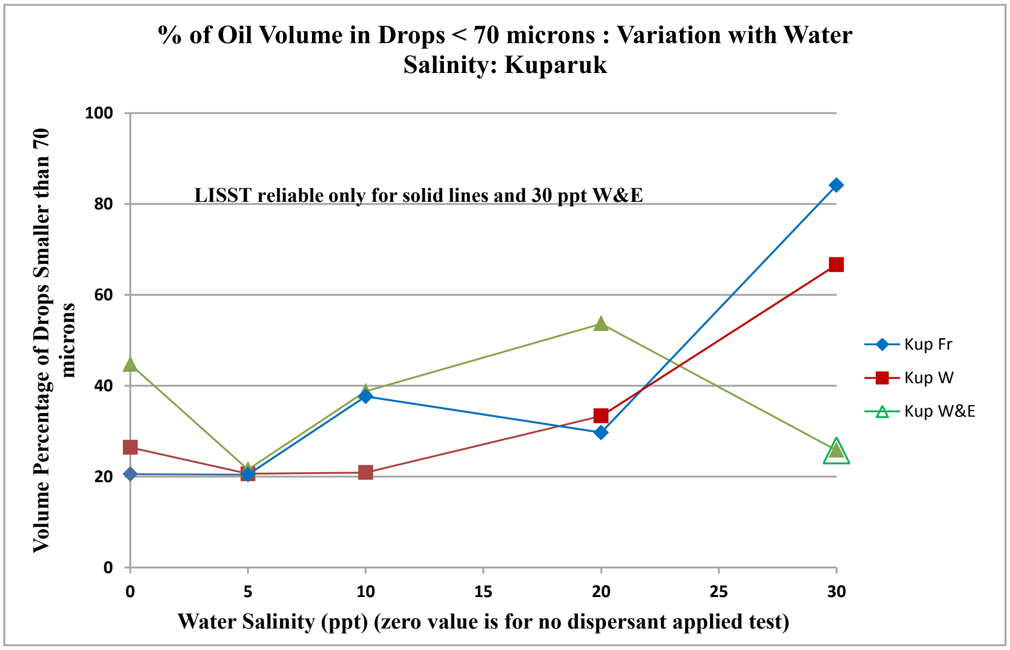


Figure 7-11 Volume Percent of Oil in Drops Less than 70 Microns: Kuparuk Crude

The LISST results for Northstar oil are summarized in Figure 7-12 and Figure 7-13. For Northstar crude the LISST data was reliable for all but the no dispersant applied control case. Tests were not conducted with Northstar crude oil at 30 ppt water salinity because the dispersant was 100% effective in dispersing the oil at 20 ppt and the dispersion generated in the 20 ppt water was a coffee colored dispersion which indicates a dispersion with a small oil drop size distribution. The oil drop VMDs for both the fresh and weathered Northstar were 70 microns or smaller for the 20 ppt salinity water as seen in Figure 7-12. About 95% of oil was present in oil drops less than 70 microns for the fresh oil and about 58% for weathered oil, as seen in Figure 7-13. The VMD oil drop sizes for the fresh oil test at 5 ppt and the weathered oil tests at 5 and 10 ppt were considerably larger (ranged between 150 and 180 microns as seen in Figure 7-12).

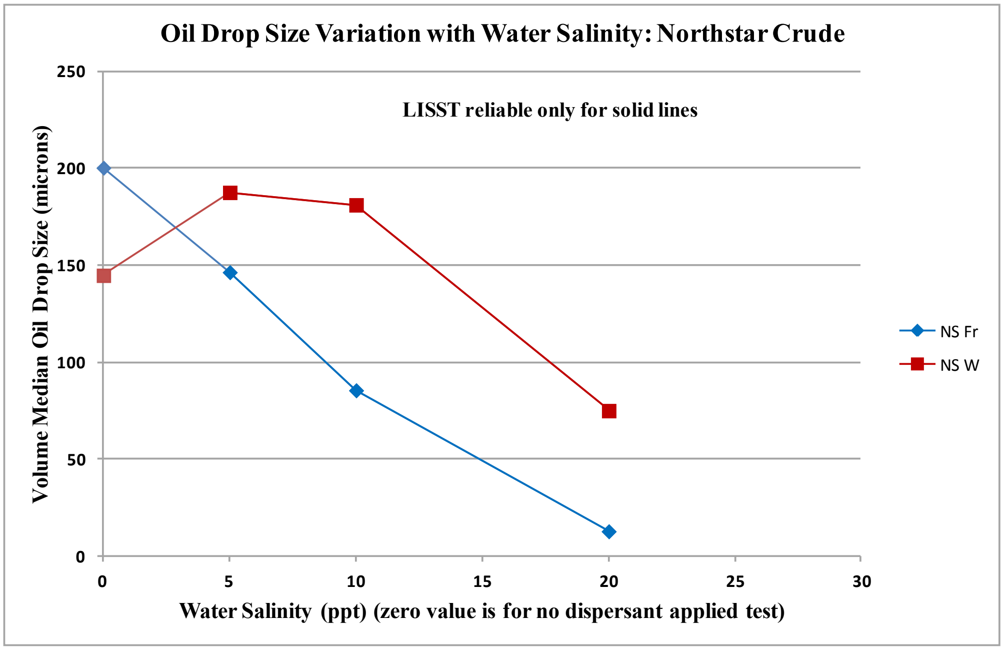


Figure 7-12 Oil Drop Size Variation Versus Water Salinity: Northstar Crude

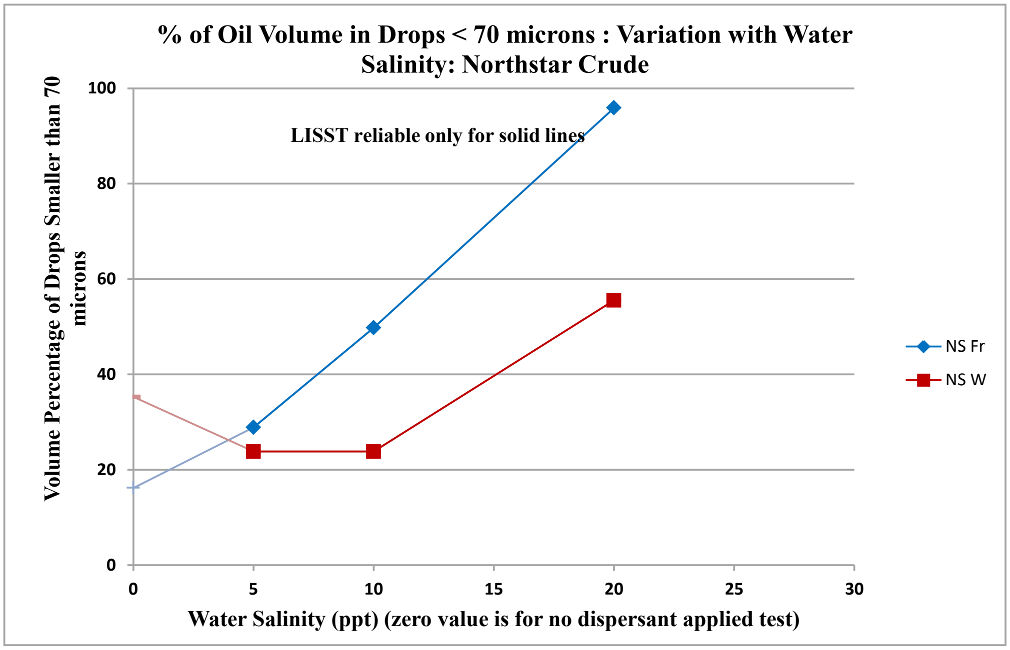


Figure 7-13 Volume Percent of Oil in Drops Less than 70 Microns: Northstar Crude

The LISST results for ANS oil are summarized in Figure 7-14 and Figure 7-15. For ANS crude the LISST data was reliable for the fresh oil tests at all salinities and at both the 20 and 30 ppt water salinity for the weathered oil. The LISST data was not reliable for any of the control tests (no dispersant applied) or for any of the W&E tests. The oil drop VMDs for the fresh oil were about

25 microns and for the weathered ANS were about 125 microns for the 30 ppt salinity water as seen in Figure 7-14. About 90% of the oil was present in oil drops less than 70 microns for the fresh ANS test at 30 ppt but only 30 % for the weathered oil test (see Figure 7-15). In the 20 ppt salinity water tests the VMD oil drop sizes were about 60 microns in the fresh oil test and 160 microns with the weathered oil (Figure 7-14). In the 10 ppt water salinity tests for ANS the oil drop VMD increased to about 160 microns, similar to the weathered oil value at 20 ppt. The oil drop VMD increased to nearly 200 microns in the 5 ppt water salinity test.

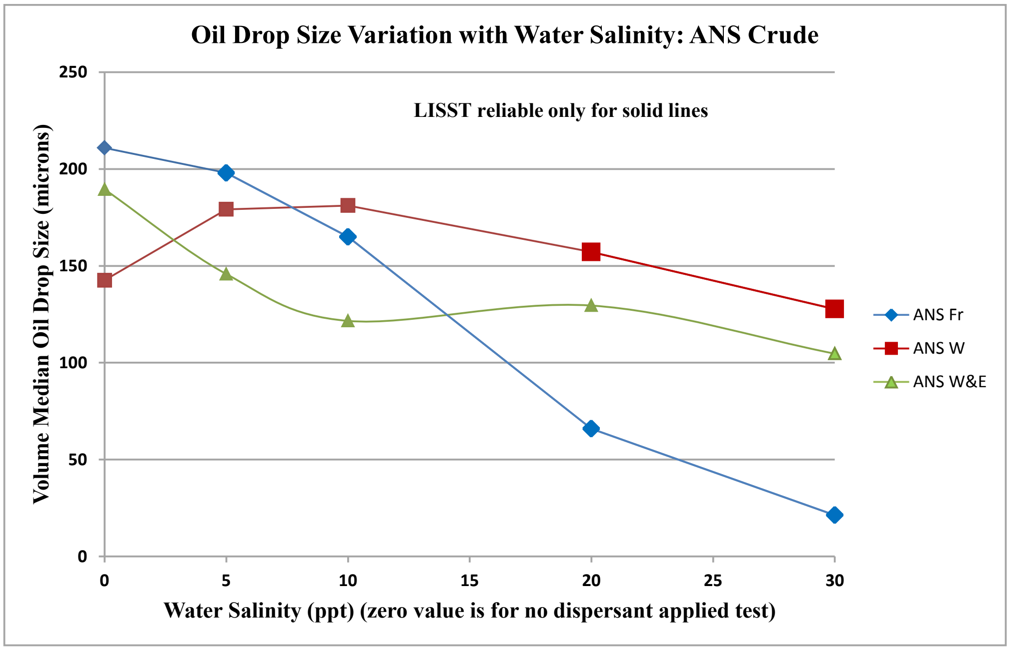


Figure 7-14 Oil Drop Size Variation Versus Water Salinity: ANS Crude

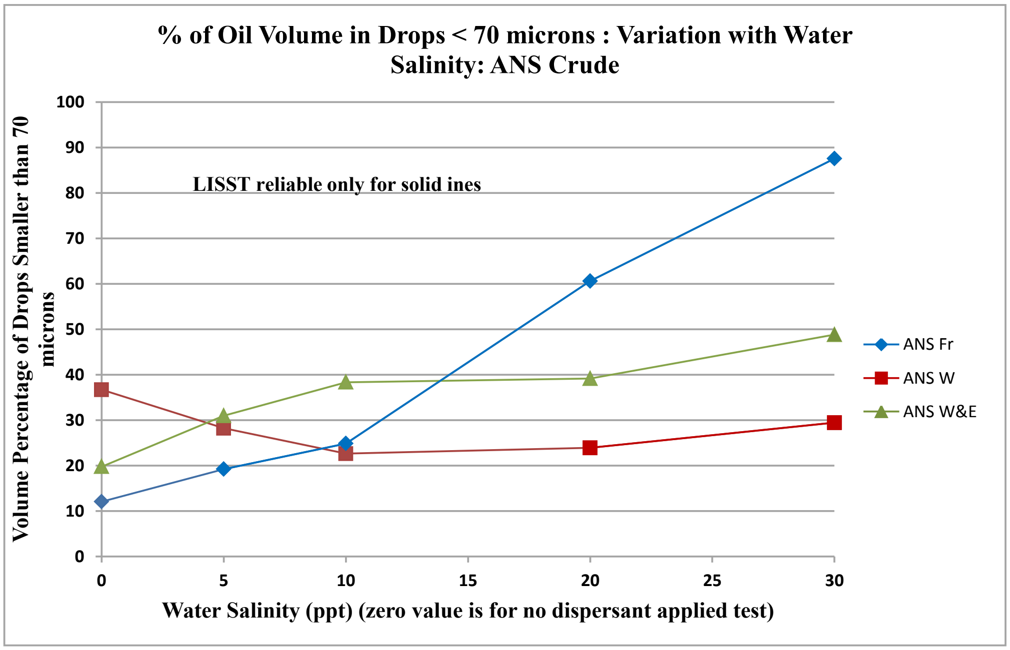


Figure 7-15 Volume Percent of Oil in Drops Less than 70 Microns: ANS Crude

7.4.3 Drop Size Adjusted Dispersant Effectiveness Estimates

The raw dispersant effectiveness (DE_{raw}) estimates presented in section 7.4.1 have been adjusted by multiplying the DE_{raw} values by the volume fraction of oil present in drops smaller than 70 microns. The 70 micron drop size value has been reported as being the maximum oil drop size that will remain dispersed based on field tests that utilized 7 different pre-mixed oil and dispersant combinations and wind conditions varying from 1.5 m/s to 7 m/s (Lunel, 1993). A second set of adjusted dispersant effectiveness results has been prepared using a 125 micron oil diameter cutoff to demonstrate the sensitivity of the estimate to the cutoff drop diameter. The 125 micron cutoff has been used based on additional accounts that have indicated that oil drops larger than 70 microns (100 microns) can remain dispersed (Neff 1990). It is possible that in heavier seas larger oil drops would be dispersed for long enough periods that even if they re-surfaced they would form sheens and not reform into thick slicks. The drop size data used to generate these adjusted DE values are strictly reliable only for the solid line and large open symbol data shown on these figures due to the upper limit of drop size detectability of the LISST device used to measure the drops, as was previously discussed. For those cases where the LISST data are not reliable (dashed lines) the adjusted DE estimates are likely higher than the actual adjusted effectiveness would be because the LISST is not registering the presence of large oils drops which would result in a lower volume fraction of the oil being present in the small drop size categories.

The un-adjusted or raw DE graphs presented in 7.4.1 are duplicated in this section and shown on the same page as the adjusted DE graphs for easy comparison of the results. The 70 micron adjusted dispersant effectiveness (DE_{70}) values are generally lower than the raw DE values. The lower water salinity tests also generally had a greater reduction in DE when compared to the 30 ppt tests. Since many of the low salinity tests also had drop sizes outside of the range of the LISST device the adjusted DE values reported are also likely exaggerated. This would indicate that significantly larger oil drops than 70 microns are being removed from the containment zone in the SL Ross wave tank and that larger oil drops were generally formed as the water salinity decreased. When the oil drop size diameter cutoff for successful dispersion is relaxed to 125 microns the DE_{125} estimates generally increase by about 15 to 20% across all oils and water salinities but there was still a significant reduction in dispersant effectiveness compared to the unadjusted values.

The Endicott crude was the most difficult to disperse of the 4 oils. The adjusted DE_{70} of the fresh and weathered Endicott were only 40 and 30 %, respectively (see Figure 7-17). For the fresh Endicott there was a linear reduction in DE_{70} as the water salinity decreased. The DE_{70} in 5 ppt salt water was 18%.

For the Kuparuk crude the fresh and weathered DE_{70} values were about 85% and 65%, respectively (see Figure 7-20). The reduction in DE_{70} as the salinity decreased was again linear if the 20 ppt fresh oil value is treated as an outlier. The rate of decrease in effectiveness for Kuparuk was higher than for the Endicott. The DE_{70} in 5 ppt salt water was 20ppt, similar to the Endicott value. The weathered Kuparuk DE_{70} is slightly less than the fresh DE_{70} and reduced with declining salinity at a similar or slightly higher rate.

For the Northstar crude oil, the lightest product tested, the fresh oil DE_{70} at 20 ppt (the highest water salinity tested with this oil) was about 95%. The DE_{70} again dropped linearly, as the salinity decreased, to a value of about 30% in 5 ppt salt water (see Figure 7-23). The weathered Northstar DE_{70} was about 75% in 20 ppt water and dropped to 40% in both 10 and 5 ppt salt water.

The ANS DE_{70} for fresh oil in 30 ppt salt water was over 90% and again decreased linearly to about 20% in 5 ppt water (see Figure 7-26). The weathered ANS DE_{70} was only 50% in 30 ppt salt water and dropped to below 30% in 20 ppt water.

The highest DE_{70} recorded for any of the emulsified oils was 20% in 30 ppt salt water.

When the oil drop size diameter cutoff for successful dispersion is relaxed to 125 microns the DE_{125} estimates generally increase by about 15 to 20% across all oils and water salinities when compared to the DE_{70} values. This is strictly a result of an additional 15 to 20% of the oil in the dispersion being present in drops with sizes between 70 and 125 microns.

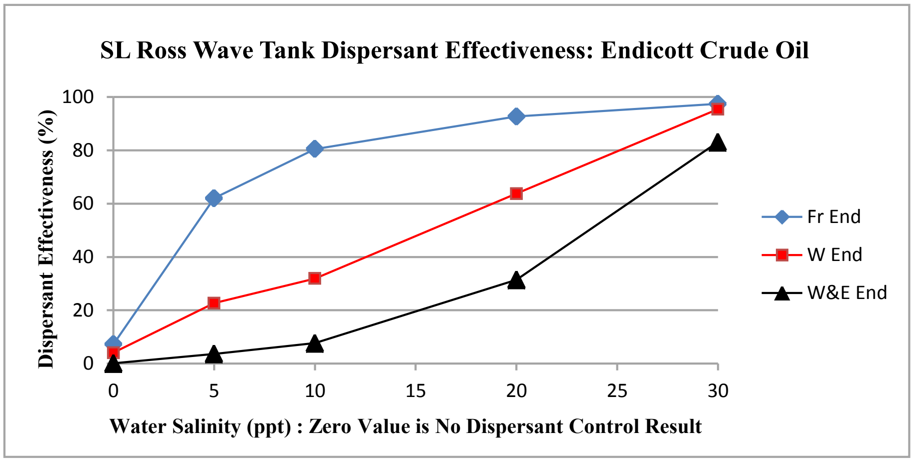


Figure 7-16 Dispersant Effectiveness versus Water Salinity: Endicott Crude Oil (copy of Figure 7-4)

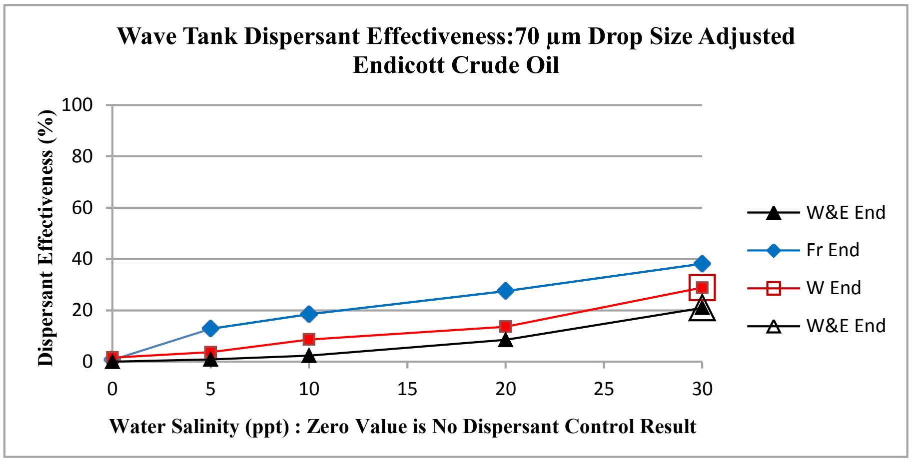


Figure 7-17 Drop Size Adjusted (70µm) Dispersant Effectiveness versus Water Salinity: Endicott Crude Oil

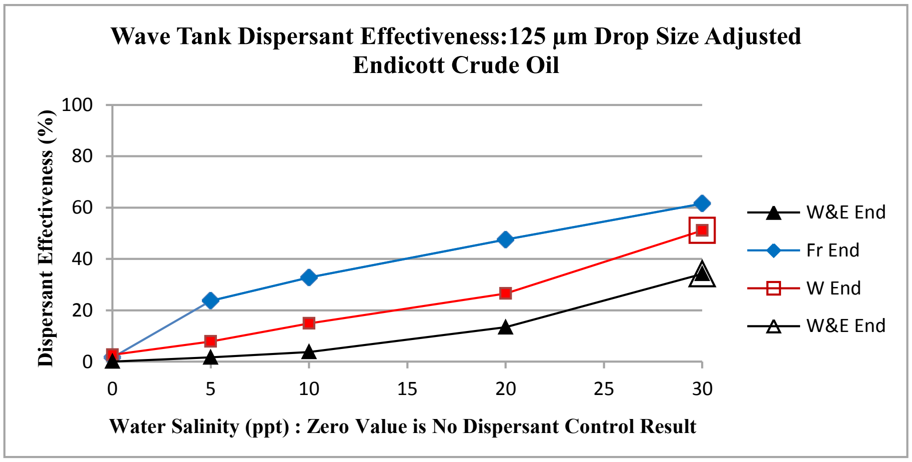


Figure 7-18 Drop Size Adjusted (125µm) Dispersant Effectiveness versus Water Salinity: Endicott Crude Oil

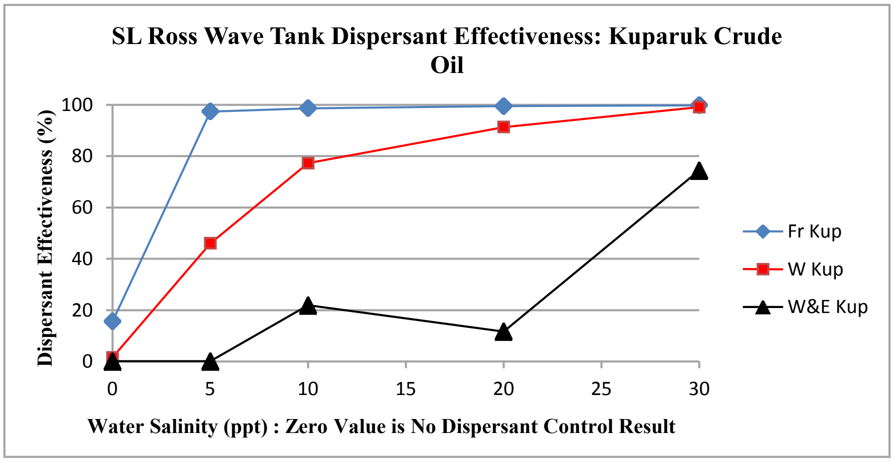


Figure 7-19 Dispersant Effectiveness versus Water Salinity: Kuparuk Crude Oil (copy of Figure 7-5)

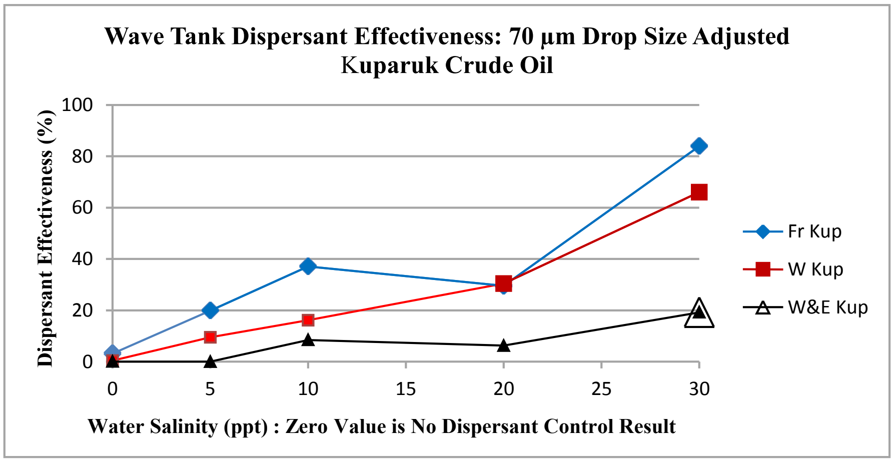


Figure 7-20 Drop Size Adjusted (70µm) Dispersant Effectiveness versus Water Salinity: Kuparuk Crude Oil

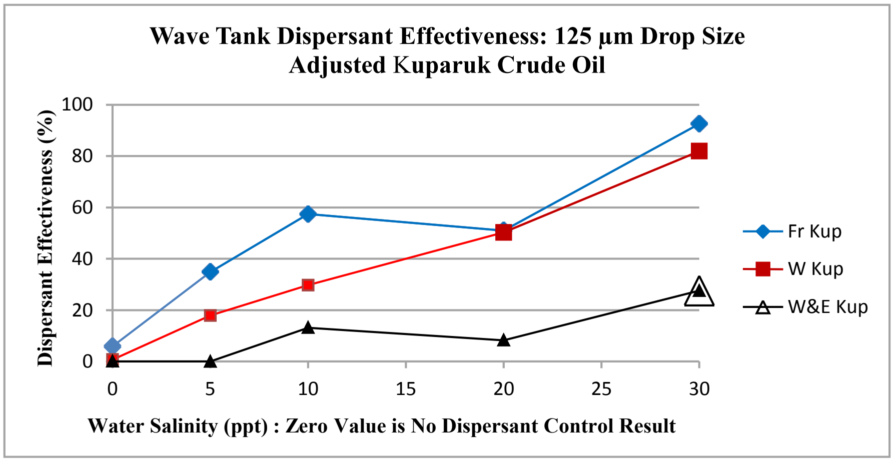


Figure 7-21 Drop Size Adjusted (125µm) Dispersant Effectiveness versus Water Salinity: Kuparuk Crude Oil

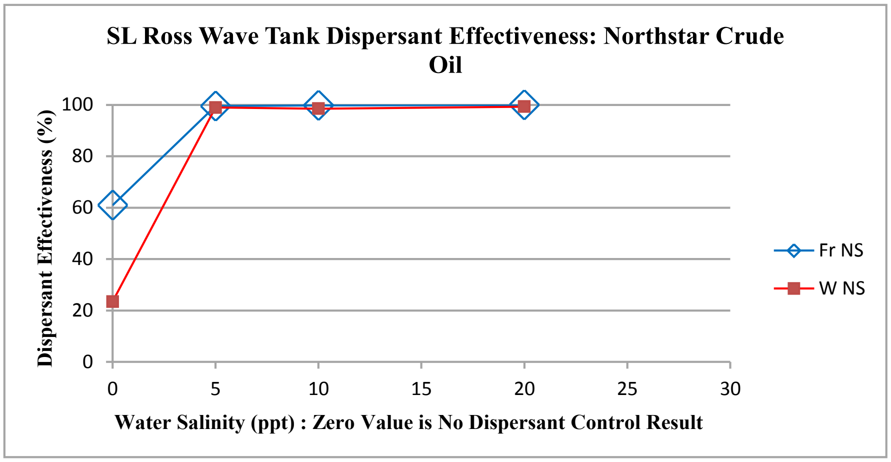


Figure 7-22 Dispersant Effectiveness versus Water Salinity: Northstar Crude Oil (copy of Figure 7-6)

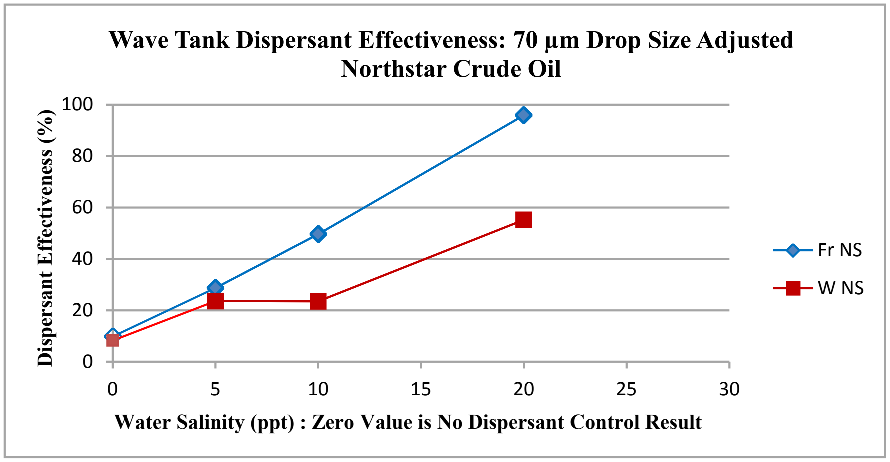


Figure 7-23 Drop Size Adjusted (70µm) Dispersant Effectiveness versus Water Salinity: Northstar Crude Oil

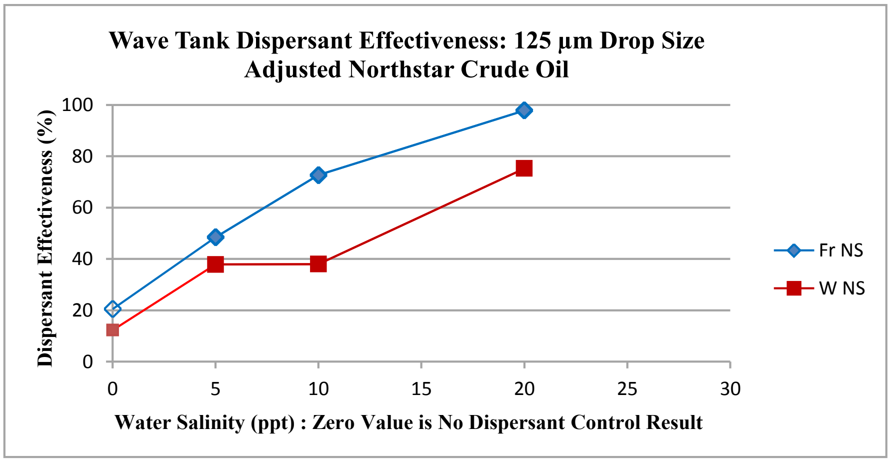


Figure 7-24 Drop Size Adjusted (125µm) Dispersant Effectiveness versus Water Salinity: Northstar Crude Oil

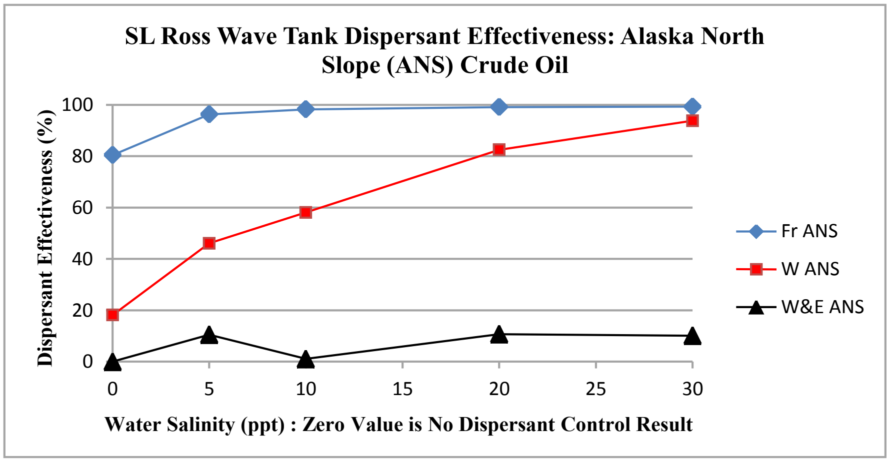


Figure 7-25 Dispersant Effectiveness versus Water Salinity: ANS Crude Oil (copy of Figure 7-7)

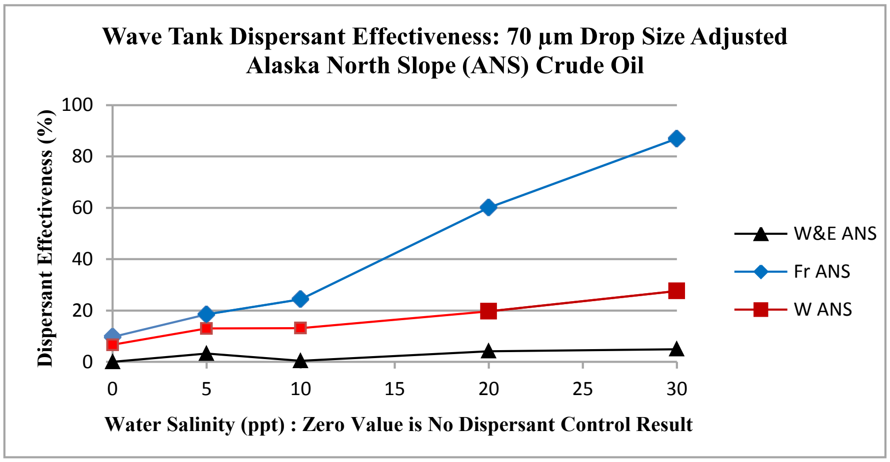


Figure 7-26 Drop Size Adjusted (70µm) Dispersant Effectiveness versus Water Salinity: ANS Crude Oil

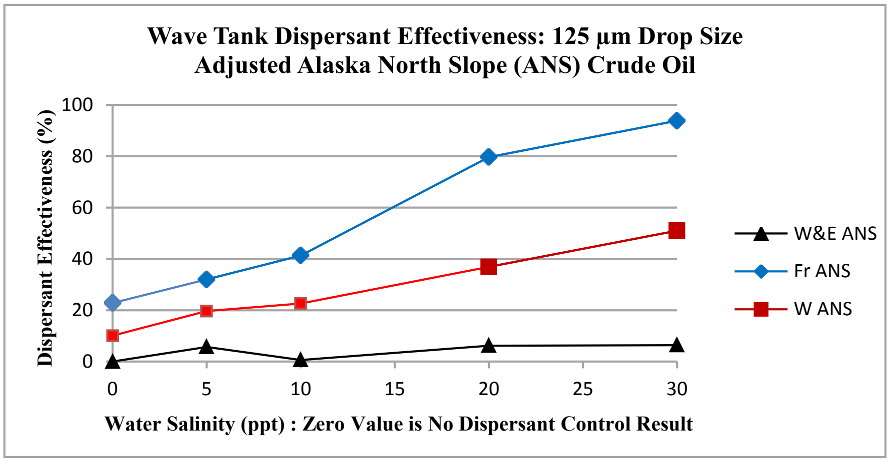


Figure 7-27 Drop Size Adjusted (125µm) Dispersant Effectiveness versus Water Salinity: ANS Crude Oil

7.4.4 SL Ross Tank Test Results Discussion

The dispersant had an effect on all of the oils at all water salinities (5 through 30 ppt) when compared to the no dispersant applied control case. The oil drops sizes in the dispersions increased as the salinity decreased demonstrating the reduced effect of the Corexit 9500 dispersant on the oils at lower water salinities.

Final dispersant effectiveness estimates (DE_{70}) were made by adjusting the quantity removed from the surface by the volume percent of oil present in drops less than 70 microns.

The most complete data sets collected (due to limitations of the LISST in measuring large oil drops) were for the fresh oil tests. The results for the fresh oils indicate that the DE_{70} values are highest for the 30 ppt water and in all cases drop linearly as the test water salinity decreased to 5 ppt. The Northstar crude was most easily dispersed with complete dispersion (> 95% DE_{70} in 20 ppt salt water), followed by fresh ANS (95% DE_{70}), fresh Kuparuk (85% DE_{70}) and Endicott (40% DE_{70}). The DE_{70} dropped linearly to between 15 to 25 % for the oils tested as the water salinity decreased to 5 ppt.

An alternate DE_{125} was also estimated using a 125 micron cutoff to demonstrate the sensitivity of the drop size cutoff for permanent dispersion on the final DE estimate. The 125 micron value was arbitrarily chosen as a significantly larger drop diameter to investigate the effect on the estimated DE. The DE_{125} estimates generally increase only by about 15 to 20% across all oils and water salinities when compared to the DE_{70} values. The same trends in DE with water salinity and oil type are present in the DE_{125} results.

The oil drops in some of the tests were visibly larger than the upper measurement limit of the LISST device and reliable drop size data could not be gathered for these tests. Development of an in-situ oil drop measurement system capable of cost-effectively measuring drop sizes in the 10 to 3000 micron range would improve the state-of-the art in oil dispersion monitoring both in large tank and field test conditions.

The SL Ross wind wave tank was outfitted with a new computer controlled paddle and wave dampening beaches in 2013. This upgrade now permits the creation of breaking waves at a specific location and with a specific frequency and wave height. In the tank's previous configuration the wave generation was limited to a confused sea type of motion with no significant plunging wave activity. Dispersant effectiveness test results in the old wind-wave facility have correlated well with results collected in the Ohmsett wave tank (SL Ross 2003). This is the first extensive series of tests conducted in the new facility with the use of the plunging or breaking waves that have been described in Section 7.2. There was no visible loss of oil from the containment zone at the surface of the tank during the tests. The breaking waves did propel significant quantities of small and large oil drops into the upper 2/3 of the water depth when the oil was fresh and relatively non-viscous. In tests conducted with the old tank configuration large oil drops were not driven as deep into the water column and then re-surfaced more quickly than in the breaking wave environment. This provided less time for the sub-surface movement of the larger oil drops out of the containment zone. This is the likely reason for the high unadjusted dispersant effectiveness results in the tests where the oil drop sizes were significantly greater than 70 microns. Due to the presence of multiple beach elements in the tank it is not possible to collect oil surfacing outside of the bubble containment zone. Based on the experience gained in this test program we recommend that smaller breaking waves be used in future tests to minimize the depth of penetration of oil in each breaking event and minimize the loss of large dispersed oil drops from the containment region.

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9 Appendix A : Detailed Dispersant Effectiveness Tables

Table 9-1 Percentage of Time Dispersants Would Be Effective at Wind Station 2 (Chukchi Sea Offshore Wainwright)

Percent of Time Dispersants Effective (48 hour Calm Wind Grace Period)						
	31 year Data Analysis (1979 to 2009)			10 year Data Analysis (2000 to 2009)		
Month	Favorable	Impaired	Not Favorable	Favorable	Impaired	Not Favorable
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	77	2	21	77	2	21
7	83	2	15	83	2	15
8	90	2	7	87	3	10
9	89	6	5	90	5	4
10	86	9	5	88	9	3
11	80	9	11	82	9	9
12	0	0	0	0	0	0

Table 9-2 Percentage of Time Dispersants Would Be Effective at Wind Station 3 (Beaufort Sea Offshore Barrow)

Percent of Time Dispersants Effective (48 hour Calm Wind Grace Period)						
	31 year Data Analysis (1979 to 2009)			10 year Data Analysis (2000 to 2009)		
Month	Favorable	Impaired	Not Favorable	Favorable	Impaired	Not Favorable
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	73	2	25	76	2	22
8	82	2	15	79	3	19
9	87	3	10	87	4	9
10	81	5	14	86	6	8
11	0	0	0	0	0	0
12	0	0	0	0	0	0

Table 9-3 Percentage of Time Dispersants Would Be Effective at Wind Station 4 (Beaufort Sea Offshore Prudhoe Bay)

Percent of Time Dispersants Effective (48 hour Calm Wind Grace Period)						
	31 year Data Analysis (1979 to 2009)			10 year Data Analysis (2000 to 2009)		
Month	Favorable	Impaired	Not Favorable	Favorable	Impaired	Not Favorable
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	69	3	28	71	3	26
8	79	3	18	75	3	22
9	86	5	10	87	4	10
10	80	7	13	84	7	9
11	0	0	0	0	0	0
12	0	0	0	0	0	0

Table 9-4 Percentage of Time Dispersants Would Be Effective at Wind Station 4 (Beaufort Sea Offshore East of Barter Island)

Percent of Time Dispersants Effective (48 hour Calm Wind Grace Period)						
	31 year Data Analysis (1979 to 2009)			10 year Data Analysis (2000 to 2009)		
Month	Favorable	Impaired	Not Favorable	Favorable	Impaired	Not Favorable
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	80	2	17	81	2	17
8	82	4	14	78	4	17
9	87	4	9	87	4	10
10	82	6	13	79	6	15
11	0	0	0	0	0	0
12	0	0	0	0	0	0

10 Appendix B : Annotated Bibliography: Past Research Relevant to Dispersion of Alaskan Oils in the US Beaufort and Chukchi Seas

Abbasova, A. et al. 2005. Evaluation of dispersants for use in the Azerbaijan region of the Caspian Sea.
Oil Type: Chirag crude oil (Caspian Sea)
Dispersant Type: Finasol OSR51, Superdispersant 25, Corexit EC 9527a, Corexit EC 9500a, Slickgone NS, Inipol IP90
Water Temperature: assumed to be EPA standard temp of 23 ± 3 °C
Water Salinity: 12 ppt (Caspian Sea Water) Six dispersants were tested on Chirag crude oil in 12 ppt water. All dispersants were effective in dispersing this crude oil at this low salinity. Average effectiveness values ranged from 72 to 84%.
Presence of Ice: Not studied.
Energy Level: EPA Baffled Flask.

Anderson, J.W., D.L. McQuerry, S.L. Kiesser. 1985. Laboratory evaluation of chemical dispersants for use on oil spills at sea
Oil Type: Alaska North Slope crude
Dispersant Type: 14 different dispersants. Dose set to achieve 90 % dispersion of ANS in MNS apparatus. Primary purpose to investigate toxicity of chemically dispersed oil.
Water Temperature: 15 °C.
Water Salinity: 30 ppt
Presence of Ice: Not studied.
Energy Level: MNS standard mixing (1.0 inch of water pressure)

Belore, R., S. Ross. 2000. Laboratory study to compare the effectiveness of chemical dispersants when applied dilute versus neat
Oil Type: Alaska North Slope crude
Dispersant Type: Corexit 9500 and Corexit 9527. Dispersant was applied neat and diluted with salt water. Corexit 9527 performed as well when diluted as when applied neat. Corexit 9500's performance was reduced when applied diluted with sea water. Application of Corexit 9500 in a neat form was recommended.
Water Temperature: 17 °C
Water Salinity: 32 ppt
Presence of Ice: Not studied
Energy Level: SL Ross wave tank, energy not varied.

Belore, R. 2003. Large wave tank dispersant effectiveness testing in cold water
Oil Type: fresh and weathered Alaska North Slope and Hibernia crude
Dispersant Type: Corexit 9500 and Corexit 9527.
Water Temperature: -0.5 to 2.4 °C. Both oils were readily dispersed by both dispersants at the cold test temperatures.
Water Salinity: 32 ppt
Presence of Ice: Not studied
Energy Level: Ohmsett breaking wave conditions. The average wave amplitude for the tests ranged between 16.5 and 22.5 cm and the average wave period was between 1.7 and 1.9 seconds.

Blondina, G., M Singer, I. Lee, M. Ouano, M. Hodgins, R. Tjeerdema. 1999. Influence of Salinity on Petroleum Accommodation by Dispersants.
Oil Type: various including Prudhoe Bay crude
Dispersant Type: Corexit 9500 and Corexit 9527
Water Temperature: 15 °C
Water Salinity: 0 to 35 ppt. For Prudhoe Bay crude oil 9500 was equally effective from 20 to 35 ppt and effectiveness dropped off below 20 ppt. 9527 effectiveness dropped off below 30 ppt.
Presence of Ice: Not studied
Energy Level: modified Swirling Flask test.

Brandvik, P.J., 0.0. Knudsen, M.O. Moldestad and P.S. Dating, 1995. Laboratory Testing of Dispersants Under Arctic Conditions
Oil Type: Norwegian Crude Oils
Dispersant Type: Corexit 9500 & 9527 plus 12 others, 5 main dispersants tested were Inipol IPF, Inipol IPC, Enersperse 700, Finasol OSR-52 and Dasic Fresh Water.
Water Temperature: 0°C
Water Salinity: 5 to 35 ppt. Dispersants formulated for low salinity performed well at low salinities but not at high salinities. Traditional dispersants formulated for high salinity water did not perform well at low salinities. Many dispersants performed well at the low test temperature on most of the oils tested but effectiveness was a function of the oil type.
Presence of Ice: Not studied
Energy Level: IFP test, energy not varied

Brown, H.M., R.H. Goodman. 1985. Dispersant Effectiveness in Cold Water
Oil Type: Federated crude (Alberta Sweet Mixed Blend)
Dispersant Type: Corexit 9527, and CRX-8.
Water Temperature: -2 °C.
Water Salinity: Tests were conducted at 28 ppt water salinity
Presence of Ice: Slush ice present in test #6 only
Energy Level: Low energy non-breaking waves were used. In 20 cm waves 24 to 33% of the spilled oil was dispersed in the water column even 20 hours after the wave basin energy had been stopped. The single test conducted with slush ice resulted in more oil dispersion than in open water. This was attributed to the shear imparted by the moving slush ice

Brown, H.M., R.H. Goodman. 1987. Outdoor Wave Tank Tests
Oil Type: Alaska North Slope Crude (ANS) weathered 12 to 24 hours on tank prior to dispersant application.
Dispersant Type: Corexit 9527, 9550 and Enersperse 700 were tested. Enersperse was least effective 38% and Corexit 9527 and 9550 were similar with 53 to 63% effectiveness at higher wave energy.
Water Temperature: Water temperature was not varied but tests were conducted at 0 to 5 °C.
Water Salinity: Tests were conducted at 32 ppt water salinity
Presence of Ice: Not studied
Energy Level: The single test conducted with lower wave energy had 19% less effectiveness than the higher energy test (42% versus 61%).

Brown, H.M., D.K.Weiss, R.H. Goodman. 1990. Emulsion formation in dispersant-treated crude oil.

Oil Type: Alaska North Slope and Drift River crude

Dispersant Type: Corexit 9500 and Corexit 9527. For the non-dispersed portions of slicks of Drift River crude, the application of dispersants enhanced the rate of water incorporation and also increased the viscosity, while the opposite effect was observed for North Slope crude oil: the treated slicks did not emulsify as fast or achieve as high viscosities.

Water Temperature: -not reported

Water Salinity: 30 ppt

Presence of Ice: Not studied

Energy Level: Esso wave basin. The average wave amplitude for the tests was 20 cm and the average wave period was between 1.6 seconds.

Brown and Goodman 1996. The Use of Dispersants in Broken Ice

Oil Type: Federated crude oil

Dispersant Type: Corexit 9527, 9500

Water Temperature: -1.2 °C

Water Salinity: Tests were conducted at 30 ppt water salinity

Presence of Ice: Condition 1: Five-metre diameter booms were positioned and frozen into the ice. Before oil was spilled into the boomed area, low amplitude waves were generated to break the ice. Several such experiments were conducted involving different ice thicknesses and ice coverages. In all cases oil was effectively dispersed (>90% dispersion) even in 95% ice cover and low wave levels

Condition 2: Ice slot was cut into fully formed ice sheet. Oil was placed in the slot. No measureable natural dispersion occurred under low energy with no ice present. With slush ice present some natural dispersion occurred. When dispersant was added to oil in slush ice almost all oil dispersed

Energy Level: Low energy swells by wave board in ESSO outdoor wave basin.

Byford, D., P. Green, A. Lewis. 1983. Factors Influencing the Performance and Selection of Low-Temperature Dispersants.

Oil Type: Lago Medio, North Slope Crude, Medium Fuel Oil

Dispersant Type: Corexit 9527, Corexit 9550 BP1100WD, Fiansol OSR5, Dispolene 34S, Arcochem D609

Water Temperature: 0 and 10 °C. In all cases the dispersant performance was not reduced in the lower temperatures and in some cases was enhanced.

Water Salinity: 0 to 33 ppt. Water salinity was found to affect dispersant performance to varying degrees. One product worked equally as well at all salinities but was a poor performer compared to other products. Product names were not attached to results.

Presence of Ice: 100% broken ice pieces (5 mm x10mmx10mm) in BP wave tank tests. Results suggest that dispersant performance can be enhanced due to the enhanced mixing caused by the pumping action between ice pieces. Dispersion was at least as good in ice conditions as in open water in all tests.

Energy Level: standard WSL test and BP wave tank with 40 mm wave amplitude

Chandrasekar, S. G.A., Sorial, J.W. Weaver. 2003. Determining dispersant effectiveness data for a suite of environmental conditions.
Oil Type: Prudhoe Bay (PBC), South Louisiana (SLC) crude and #2 Fuel oil. Slight reduction in effectiveness was identified with weathered (10 to 20% loss) versus fresh oil. For PBC the reduction was less than 5%.
Dispersant Type: Corexit 9500 and Dispersit-SPC 1000
Water Temperature: 5, 22 and 35 °C. Increased dispersion with increased temperature for SLC, maximum dispersion at 22°C for both PBC and #2 Fuel oil.
Water Salinity: standard BF 34 ppt assumed
Presence of Ice: Not studied
Energy Level: 150, 200 and 250 rpm on shaker table. Higher effectiveness at higher energies in all tests.

Chandrasekar, S.; Sorial, G.A.; Weaver, J.W. 2006. Dispersant effectiveness on oil spills – impact of salinity.
Oil Type: Alaskan Prudhoe Bay (PBC) fresh, 10% and 20% evaporated, South Louisiana crude oil (SLC) fresh, 10% and 20% evaporated, No. 2 Fuel Oil (2FO) fresh, 3.8% and 7.6% evaporated. Weathered PBC dispersed as well as fresh at 200 rpm and over the full range of temperatures.
Dispersant Type: Dispersants identified as A & B only
Water Temperature: 5, 22 and 35 °C. Highest effectiveness at 250 rpm for the most weathered PBC was achieved at 22 °C.
Water Salinity: 10, 20, 34 ppt. Salinity did not significantly (less than 15% difference over salinity range) impact the effectiveness of dispersant A for the fresh or weathered PBC at any of the temperatures tested.
Presence of Ice: Not studied.
Energy Level: EPA Baffled Flask operated at 150, 200 and 250 rpm. Higher energy resulted in higher dispersion (all other factors constant)

Cox, J., L. Shultz 1981. Dispersant Effectiveness Under Arctic Conditions, Including Ice
Oil Type: Sadlerochit crude fresh, 10 and 30% weathered, 10% weathered Arctic diesel, 10% weathered Kuparuk crude
Dispersant Type: Identified as X,Y and Z only
Water Temperature: -0.6 °C
Water Salinity: 10, 20 and 32 ppt. results showed no difference in dispersant effectiveness over the range of salinities tested
Presence of Ice: 20 and 50% coverage of 1.5 cm thick and 5.7 cm diameter ice
Energy Level: MNS apparatus with ice present. Slight increase in natural dispersion with ice present versus open water. When dispersant was added dispersion rose substantially. No difference in results between 20% and 50% ice coverage

Fingas, M.F., I. Bier, M. Bobra and S. Callaghan. 1991. Studies on the Physical and Chemical Behaviour of Oil and Dispersant Mixtures
Oil Type: Alberta Sweet Mixed Blend, Norman Wells, Adgo
Dispersant Type: Corexit 9527, Enersperse 700 and Citrikleen

Water Temperature: 0 to 50 °C on a subset of tests with Corexit 9527 and ASMB oil only. Dispersant effectiveness reduced with decrease in temperature.
Water Salinity: Maximum effectiveness was achieved at 40 to 45 ppt and fell sharply with either a decrease or increase in salinity for all dispersant and oil combinations tested.
Presence of Ice: Not studied
Energy Level: SF test with no variation in energy level

Fingas, M., B.Fieldhouse, Z.Wang. 2005b. The Effectiveness of Dispersants under Various Temperature and Salinity Regimesingas
Oil Type: Alberta Sweet Mixed Blend (ASMB)
Dispersant Type: Corexit 9500
Water Temperature: 0 to 25 °C on ASMB oil only. Dispersant effectiveness reduced with temperature increase above 20 °C and was similar over 5 to 20 °C contrary to most other research.
Water Salinity: Maximum effectiveness was achieved at 25 ppt and fell sharply with a decrease below 20 °C.
Presence of Ice: Not studied
Energy Level: SF test with no variation in energy level

Fingas, M., B. Fieldhouse, Z. Wang. 2006. The Effectiveness of Dispersants on Alaska North Slope Crude Oil under Various Temperature and Salinity Regimes
Oil Type: Alaska North Slope Crude (ANS)
Dispersant Type: Corexit 9500
Water Temperature: 5 to 25 °C Dispersant effectiveness reduced with temperature increase above 10 °C and was similar over 5 to 10 °C contrary to most other research where higher temperatures usually result in higher dispersant effectiveness.
Water Salinity: Maximum effectiveness was achieved at 25 ppt at all temperatures and fell sharply with water salinity below 20 ppt.
Presence of Ice: Not studied
Energy Level: SF test with no variation in energy level

Fiocco, R.J., P.S. Daling, G. DeMarco, R.R. Lessard, 1999. Advancing laboratory/field dispersant effectiveness testing
Oil Type: Alaska North Slope weathered oil and emulsions
Dispersant Type: Corexit 9500
Water Temperature: 15 °C
Water Salinity: 32 ppt assumed
Presence of Ice: Not studied
Energy Level: MNS test was run for longer duration (60 minutes from 5) to test Corexit 9500's ability to break emulsions. Successfully dispersion of emulsions measured with viscosities up to 15,000 cP and 65% water content. These data were compared to the 1997 North Sea field trial data where similar results were measured in the field for dispersion of emulsions by Corexit 9500.

George-Ares, A., R.R. Lessard, K.W. Becker, G.P. Canevari and R.J. Fiocco. 2001. Modification of the Dispersant Corexit 9500 for Use in Freshwater

Oil Type: Alaska North Slope Crude (ANS) plus 3 other South American crudes
Dispersant Type: Corexit 9500, calcium chloride modified 9500, Dasic freshwater, Enersperse 1037, Inipol IPF
Water Temperature: not reported, assumed room temperature and not varied
Water Salinity: All tests conducted using river (0 ppt) or deionized water. Corexit 9500 was modified by blending in calcium chloride solution at various concentrations (concentrations not reported) and tested with ANS crude oil. Conventional Corexit 9500 had an efficiency of 22% in fresh water. The modified Corexit 9500 had measured efficiencies of 29 to 63% depending on the quantity of calcium chloride added. Dasic fresh water was the most effective dispersant on all of the oils tested in the fresh water
Presence of Ice: Not studied
Energy Level: EXDET test with no variation in energy level

Lewis, A., A. Crosbie, L. Davies, T. Lunel. 1998. Large scale field experiments into oil weathering at sea and aerial application of dispersants.
Oil Type: Forties Blend, Alaskan North Slope crude, and IFO-180 fuel oil. ANS was emulsified to 35% water content prior to spraying
Dispersant Type: Corexit 9500 and Dasic Slickgone NS
Water Temperature: 18 °C
Water Salinity: full ocean salinity North Sea
Presence of Ice: Not studied
Energy Level: offshore conditions in 3 to 5 m/s winds with gusts 7 to 8 m/s. 30 m^3 of ANS crude, weathered for 55 h, was completely dispersed with Corexit 9500 applied from the air in two stages with a total DOR of approximately 1:12.

Li, Z., K. Lee, T. King, M. Boufadel, A. Venosa. 2009. Evaluating Crude Oil Chemical Dispersion Efficacy in a Flow-Through Wave Tank Under Regular Non-Breaking Wave and Breaking Wave Conditions
Oil Type: fresh ANS and weathered (14%) Mesa crude oil
Dispersant Type: Corexit 9500 & Dispersit SPC 1000
Water Temperature: not reported
Water Salinity: not reported
Presence of Ice: Not studied.
Energy Level: EPA /DFO wave tank operated with regular non-breaking waves, and plunging breakers. 21 to 36% of oil was dispersed and diluted with dispersants and non-breaking waves. 42 to 62% of the oil was dispersed and diluted with dispersants and plunging breakers. With no dispersants and both wave conditions only 8 to 19% of the oil was dispersed and diluted in the flow through wave tank. Drop sizes were large with regular waves and no dispersant (VMD > 300 um) and small with dispersants and breaking waves (VMD < 50 um).

Mackay, D. , R. Mascarenhas, K. Hossain, T. McGee. 1979. The Effectiveness of Chemical Dispersants at Low Temperatures and in the Presence of Ice.
Oil Type: Alberta Sour Mixed Blend and Lago Medio crude
Dispersant Type: Corexit 9527

Water Temperature: 0 to 15°C. It was concluded that the primary effect of water temperature was to lower the oil temperature and thus increase the oil viscosity. The increased oil viscosity reduced the dispersant effectiveness.
Water Salinity: 35 ppt
Presence of Ice: Ice was introduced into the hoop tank test apparatus. The effect of the ice was to dampen the waves and generally reduce effectiveness but no other significant conclusions could be drawn about the effects of the ice.
Energy Level: MNS, Hoop tank , and Calm Sea Simulation Apparatus: Hoop tank used in ice studies.

Mackay, D., Chau, Y. Poon. 1986. MNS, Rotating Flask and Hoop Tank Test Results
Oil Type: The effectiveness of was tested on Prudhoe Bay crude oil along with 11 other oils using both the MNS and a rotating flask (RF) test. The Prudhoe Bay crude dispersibility was generally higher than the average of the 12 oils tested indicating that this Alaskan oil was amenable to chemical dispersant use.
Dispersant Type: Corexit 9527, Corexit 9550 and BP MA700
MNS test results of the three dispersants tested on the Prudhoe Bay crude oil Corexit 9550 had the best performance at 71% followed by Corexit 9527 at 45.9% and BP MA 700 at 43.1%.
Water Temperature: 5 to 25° C
Study conclusions: 'There is no inherent reason to suggest that cold climate dispersion is significantly less feasible than temperate dispersion'.
'dispersion is likely to require more dispersant under these cold conditions but the extra amount is unlikely to be large except when the oils are unusually viscous, close to their pour point or waxy'.
Water Salinity: Study conclusions: 'when assessing the suitability of dispersants for use in variable salinity waters there is presently no alternative but to measure the magnitude of the salinity dependence of dispersion on a case by case basis'. The effect of salinity was most notable for Corexit 9527 in this work when compared to Corset 9550 and BP MA700. Since Corexit 9527 (and its more modern sister Corexit 9500) are the primary dispersants in use in Alaska this would suggest that water salinity may be a concern with this particular dispersant formulation.
Presence of Ice: Not investigated
Energy Level: Acknowledged the need to measure both mixing level that generates oil drops as well as the water column suspension energy. Ranked the mixing energies of the various test methods used but only speculated how these would compare to oceanic mixing levels

Mackay, D. 1995. Effectiveness of chemical dispersants under breaking wave conditions
Oil Type: Alaska North Slope weathered 5 to 20%
Dispersant Type: Corexit 9527
Water Temperature: 4.4 to 15.5 °C Increasing temperature resulted in a slight loss of effectiveness
Water Salinity: 0 to 32 ppt. The water salinity did not affect the dispersibility of the weathered ANS in the 5 to 32 ppt range in the EXDET test (this is contrary to other test results). 30 ppt in Esso wave basin.
Presence of Ice: Not studied

Energy Level: MNS, WSL, EXDET and ESSO wave basin. EXDET was small scale test chosen as being representative, quick, more reproducible and with less waste water. EXDET energy level between 10 to 16 mm amplitude did not affect results. In the turbulent wave conditions of the wave tank (15 cm amplitude 2.5 s period) effectiveness was 90 to 100% at DORs of 1:100 with significant dispersion at DORs of 1:200 and 1:300
Other Results: The author calculated how much of the Exxon Valdez oil spill might have been dispersed if the dispersant available at the time of the spill had been applied. Determined that 38% of the oil could have been dispersed.

McAuliffe, C., B. Steelman, W. Leek, D. Fitzgerald, J. Ray, C. Barker. 1981. 1979 Southern California dispersant treated research oil spills.
Oil Type: Alaska Prudhoe Bay crude
Dispersant Type: Dispersant products identified as H & J (no brand names provided)
Water Temperature: not reported. Offshore Long Beach California in September (warm water)
Water Salinity: full ocean salinity (32 ppt)
Presence of Ice: Not studied
Energy Level: Wind speed or wave heights not reported. Extensive water sampling and analysis was undertaken and significant oil was identified in the water column up to 9 m depth. Dispersant was visually very effective as well.
Results Summary: ANS Oil was dispersible by both products but dispersant H was more effective, as measured by chemical analysis of water samples under the slick. Between 5 to 78% dispersion was measured. When dispersant was applied to the thick oil rather than entire slick dispersant effectiveness values of 60 to 78% were measured. Two hour weathered crude was less dispersible than freshly treated oil.

Moles, A.L. Holland, J. Short, 2001. Effectiveness of Corexit 9527 and 9500 in Dispersing Fresh, Weathered and Emulsion of Alaska North Slope Crude Oil Under Subarctic Conditions
Oil Type: Studied Alaska North Slope Crude (ANS) fresh, weathered and emulsified. Neither dispersant was effective on the weathered oil under any conditions tested.
Dispersant Type: Corexit 9527 and 9500. Comparable results were achieved with the two dispersants. Dispersant was pre-mixed with the oil and emulsions. This may have been one of the reasons for the high effectiveness values recorded for the emulsions.
Water Temperature &Water Salinity: 3, 10 and 22°C and 22 and 32 ppt
In tests using pre-mixed Corexit 9500 and 9527 dispersants and fresh ANS crude oil in the swirling flask test dispersion was not affected by salinity (22 ppt versus 32 ppt) at high temperatures (22°C) but was at low temperatures (10°C). Dispersion levels for fresh ANS were below the detectable limits of the SF test at 3°C and both salinities for both dispersants. Authors concluded that temperature, salinity and weathering are important factors to consider when evaluating the effectiveness of dispersants with weathering having the most profound effect. The effectiveness of 9500 in 32 ppt salinity water was similar at 10 °C and 22 °C. The colder water tests with 9527 and 32 ppt salinity had lower effectiveness.
Presence of Ice: Not studied
Energy Level: Author states that the swirling flask test is a conservative test that applies relatively low mixing energy.

Moles, A., L. Holland, J. Short. 2002. Swirling Flask Test Results
Oil Type: Alaska North Slope Crude (ANS) fresh, weathered and emulsified.
Dispersant Type: Corexit 9527 and 9500. Similar results were achieve with the two dispersants. Dispersant was pre-mixed with the oil and emulsions. This may have been one of the reasons for the high effectiveness values recorded for the emulsions.
Water Temperature &Water Salinity:
In tests using pre-mixed Corexit 9500 and 9527 dispersants and ANS crude oil in the swirling flask test dispersion was not affected by salinity (22 ppt versus 32 ppt) at high temperatures (22°C) but was at low temperatures (10°C). He concluded that temperature, salinity and weathering are important factors to consider when evaluating the effectiveness of dispersants with weathering having the most profound effect. The effectiveness of 9500 in 32 ppt salinity water was similar at 10 °C and 22 °C. The colder water tests with 9527 and 32 ppt salinity had lower effectiveness.
Presence of Ice: Not studied
Energy Level: Author acknowledges that the low energy level in the swirling flask test may not be a good representation of environmental conditions

Nagarajan, K., N. Deshpande, G. Sorial, J. Weaver. 2008. Dispersant Effectiveness on Oil Spills- Empirical Correlations.
Oil Type: Alaskan Prudhoe Bay (PBC) fresh, 10% and 20% evaporated, South Louisiana crude oil (SLC) fresh, 10% and 20% evaporated, No. 2 Fuel Oil (2FO) fresh, 3.8% and 7.6% evaporated. A linear, empirical correlation between effectiveness in BF test and all parameters tested (salinity, viscosity (as a combined measure of weathering and temperature effect) and rotational speed). Final correlation parameters not reported in paper.
Dispersant Type: Dispersants identified as A (Corexit 9500) & B (Dispersit SPC 1000)
Water Temperature: 5, 10, 16, 22, 27 and 35 °C. Highest effectiveness at 250 rpm for the most weathered PBC was achieved at 22 °C.
Water Salinity: 10, 20, 34 ppt. Salinity did not significantly (less than 15% difference over salinity range) impact the effectiveness of dispersant A for the fresh or weathered PBC at any of the temperatures tested.
Presence of Ice: Not studied.
Energy Level: EPA Baffled Flask operated at 150, 200 and 250 rpm. Higher energy resulted in higher dispersion (all other factors constant), 10% evaporated PBC was shown to be effectively 80+%) dispersed at the medium and high energy levels.

Nedwed, T. , R. Belore, W. Spring, D. Blanchet. 2007. Basin scale testing of ASD icebreaker enhanced chemical dispersion of oil spills
Oil Type:. Chayvo Z6, 3 to 6% weathered by weight
Dispersant Type: Corexit 9527. Dispersant applied to oil either prior to energy addition in broken ice or oil on ice tests or after ice breaker had broken ice and exposed the oil for treatment.
Water Temperature: Air temp 0 to -10 °C
Water Salinity: 32 ppt
Presence of Ice: Ice present in 25% to 100% ice sheet. Oil spilled in broken ice, on top of a full ice sheet and under a full ice sheet.
Energy Level: SL Ross wave tank with trolling motor prop wash. Greater than 90% effectiveness in ice cover ranging from 25% to 90%. Low dose (1:110 also effective. Prop wash

was effective on oil weathered for 98 hours. In AKER ice basin tests all energy was provided by the prop wash of a scale model azimuthal stern drive icebreaker. Dispersant effectiveness values of between 70% and 97% were measured in the tests. Oil drop VMD (d50) of 10 to 75 µm were measured in the tests indicating effective long term dispersion. Oil did not clear the tank after many weeks of sitting with no energy addition indicating long term dispersion even under quiescent conditions.

Owens, C.K.R. Belore, 2004. Dispersant effectiveness testing in cold water and brash ice.
Oil Type: Alaska North Slope, Hibernia, Chayvo crudes fresh and evaporated
Dispersant Type: Corexit 9527
Water Temperature: -0.6 to 0.9 °C
Water Salinity: 32 ppt
Presence of Ice: Yes, brash ice in 4/10 and 8/10 coverage. Higher dispersion was evident in the tests with ice cover when compared to open water at the non-breaking wave, low energy conditions tested for both fresh and weathered ANS and Hibernia crude.
Energy Level: Two wave settings used. Low: 17 cm average wave height with a 5.5 second period. High: 33 cm average wave height with a 4 second period. In low ice concentrations the higher mixing energy was needed to achieve the same dispersion as in the high ice cover, low energy tests.

Payne, J.R. et al. 1985. Estimating dispersant effectiveness under low temperature-low salinity conditions
Oil Type: Alaskan Prudhoe Bay crude oil
Dispersant Type: Corexit 9550, Finasol OSR-7, EC. O ATLANT'TOL AT-7, and OFC D-609 (AT-7 and OSR-7 were significantly less effective than others under all test conditions)
Water Temperature: 1 and 10 °C
Water Salinity: 0, 18 and 33 ppt. Corexit 9550 had best performance (>50% at 1°C, 42 % at 10 °C) at 0 ppt. D-609 outperformed Corexit 9550 at 18 ppt. Corexit 9550 and D-609 were equally effective at 33 ppt.
Presence of Ice: Not studied.
Energy Level: Used an old EPA protocol test (pre- Swirling Flask)

SL Ross. 2002. Dispersant Effectiveness Testing in Cold Water and Broken Ice
Oil Type: fresh and air sparged (evaporated) Alaska North Slope and Hibernia crude oil
Dispersant Type: Corexit 9500 & 9527.
Water Temperature: -0.5 to 2.4°C in open water -0.6 to 0.9°C in ice tests.
Water Salinity: 30 to 32 ppt
Presence of Ice: Broken ice with 50 % and 80% coverage. In open water tests DE of ANS fresh and weathered to 20% loss ranged from 96 to 99%. In ice cover tests DE of fresh and 10% weathered ANS in 8/10th ice >95%, for 20% weathered ANS DE was 22% with no ice, 30% with 4/10ths ice and 54% with 8.10ths ice. Presence of larger amounts of ice increased dispersion. DOR's ranged from 1:81 to 1:31.
Energy Level: Low energy swells (7.5 inch stroke and 10, 12 and 16 cycles /min) in ice tests, standard Ohmsett breaking waves (3.0 inch wave paddle stroke and 35 cycles per minute) in open water tests. DE in open water tests on fresh, 10% and 20% weathered ANS was >96% in all cases.

SL Ross, MAR Inc. 2003. Dispersant Effectiveness Testing on Alaskan Crude Oils in Cold Water

Oil Type: fresh and air sparged ANS, Endicott, Northstar, Cook Inlet Middle Ground Shoals and Pt. McIntyre crude oils
Dispersant Type: Corexit 9500 & 9527. Ohmsett tests used only Corexit 9527.
Water Temperature: -1.1 to -0.4 °C. In Ohmsett tests Corexit 9527 was effective on all but two fresh and weathered oils at the low temperatures (74 to 86% DE). The 29% weathered Northstar and 11% weathered Endicott had DE of only 8% and 3%, respectively.
Water Salinity: 30 ppt
Presence of Ice: Not studied.
Energy Level: SL Ross wave tank tests and Ohmsett standard dispersant effectiveness test energy level with 3.5 inch paddle stroke and 34 cycles per minute. The SL Ross wave tank tests resulted in lower DE measurements for the fresh Endicott crude oil than the Ohmsett tests (8 to 33% versus 74% at Ohmsett) likely due to energy level differences.

SL Ross. 2006. Dispersant Effectiveness Testing On Water-In-Oil Emulsions At Ohmsett.

Oil Type: fresh, air sparged and emulsions of Endicott, IFO 30, IFO 120 and Sockeye crude
Dispersant Type: Corexit 9527 and 9500.
Water Temperature: 0.6 to 3.3°C at Ohmsett, 9°C in SLR tank. Fresh Endicott dispersed 66% in SLR tank: 6% weathered and emulsion 3 and 3.3% DE. On-tank formed Endicott emulsion (~4000 cP) dispersed 10 to 35%. Mechanically formed emulsion (~6000cP) 0 to 20% DE.
Water Salinity: 30 to 32 ppt
Presence of Ice: Not studied.
Energy Level: Ohmsett standard dispersant effectiveness test energy level with 3.5 inch paddle stroke and 34 cycles per minute. SL Ross wave tank standard dispersant effectiveness test wave energy.

SL Ross & MAR Inc. 2006b. Dispersant Effectiveness Testing in Cold Water on Four Alaskan Crude Oils

Oil Type: fresh, air sparged and on tank weathered ANS, Endicott, Northstar and Pt. McIntyre crude oils
Dispersant Type: Corexit 9527.
Water Temperature: 2.8 to -2.8 °C. Dispersant was effective on all fresh and weathered oils at the low temperatures (85 to 99% DE). Weathered oil effectiveness was much higher in the 2006 vs 2003 test series possibly due to oil property differences (pour point issue?)
Water Salinity: 30 ppt
Presence of Ice: Not studied.
Energy Level: Ohmsett standard dispersant effectiveness test energy level with 3.5 inch paddle stroke and 34 cycles per minute

SL Ross, MAR Inc. 2009. Low-Dose Repeat-Application Dispersant Testing

Oil Type: ANS, Endicott, Oseberg, Rock, Ewing Bank crude oils and IFO 30 fuel oil
Dispersant Type: Corexit 9500 applied in repeat (up to 5 passes) applications of small doses (aircraft application rate) similar cumulative dispersion with multiple small doses compared to one single high dose. DE for the two Alaskan oils ranged from 88 to 95%.

Water Temperature: 16 to 18°C.
Water Salinity: 30 ppt
Presence of Ice: Not studied.
Energy Level: SL Ross Wave tank and Ohmsett standard effectiveness tests, 3.5 inch stroke, 34 cycles/minute.

SL Ross. 2010. Literature Review of Chemical Oil Spill Dispersants and Herders in Fresh and Brackish Waters
Oil Type: various including Alaska North Slope crude
Dispersant Type : various
Water Temperature: various
Water Salinity: 0 to 40 ppt. Review concluded that dispersants designed for use in marine waters are less effective when salinity falls below 20 ppt or rises above 40 ppt. Fresh water formulations work better in fresh water conditions but provide best results in water with salinities between 10 and 20 ppt
Presence of Ice: Not studied
Energy Level: Not studied

SL Ross, MAR Inc. 2011. Comparison of Large-Scale (Ohmsett) and Small-Scale Dispersant Effectiveness Test Results
Oil Type: Endicott, ANS plus 12 other crude oils
Dispersant Type: Corexit 9500
Water Temperature: 14 to 16°C. Endicott was 95% dispersed with 1:22 DOR at Ohmsett
Water Salinity: 30 to 32 ppt
Presence of Ice: Not studied.
Energy Level: Ohmsett standard dispersant effectiveness test energy level with 3.5 inch paddle stroke and 34 cycles per minute. WSL, Exdet, SF and BF
Fresh Endicott: Ohmsett DE 95%,WSL 27%, BF 80%, SF 62%, Exdet 86%
Endicott 19% evap. : Ohmsett DE 94%,WSL 18%, BF 72%, SF 42%, Exdet 90%
ANS fresh: Ohmsett DE 98%,WSL 28%, BF 76%, SF 67%, Exdet 92%
ANS 0% evap.: Ohmsett DE 97%,WSL 27%, BF 82%, SF 49%, Exdet 88%

Smith, D., G. Holliday. 1979. API/SC-PCO Southern Californian1978 Oil Spill Test Program
Oil Type: Alaska North Slope Crude
Dispersant Type: code named H & J
Water Temperature: warm water
Water Salinity: full ocean salinity
Presence of Ice: Not studied
Energy Level: natural offshore conditions in 4 to 18 knots
Results Summary: ANS Oil was dispersible by both products.

Sorial, G.A.K.M. Karen, H. Edith, A.D. Venosa, D.W. King. 2001. Development of a rational oil spill dispersant effectiveness protocol
Oil Type: Alaskan Prudhoe Bay and South Louisiana crude oil
Dispersant Type: 18 dispersants tested, results not tied to specific dispersant

Water Temperature: assumed to be EPA standard temp of 23 ± 3 °C
Water Salinity: synthetic sea water (salinity not reported but assumed to be BF standard of 34 ppt)
Presence of Ice: Not studied.
Energy Level: Swirling Flask and EPA Baffled Flask. Baffled Flask results were more reproducible than SFT and resulted in a significantly higher estimate of dispersant effectiveness for a given oil and dispersant combination. Higher effectiveness is attributed to a higher mixing energy in the BF test. The fresh Prudhoe Bay crude oil tested was highly dispersible in the BF tests (>80%) by 10 of the 18 dispersants tested

Sørstrøm, S.E., Per Johan Brandvik, I. Buist, P. Daling, D. Dickins, L. Faksness, S.Potter, J. Rasmussen and I. Singsaas.2010. Joint industry program on oil spill contingency for Arctic and ice covered waters: Summary Report
Oil Type: Troll B, 30 min weathered on water prior to dispersant application, 6 hour weathered, 6 and 7 day weathered
Dispersant Type: Corexit 9500 , Dasic Slickgone NS
Water Temperature: Not reported but in the presence of an ice field: ~ -1°C.
Water Salinity: not reported
Presence of Ice: Yes. Field ice coverage of 70-80%, 80-90%.
Energy Level: Low natural energy situation at pack ice edge. Energy applied by boat thrusters and high pressure water jets after dispersant application. Dispersant efficiency was estimated to be > 90% in all three tests. Oil drop sixes measured were in the 5 to 30 um range.

Strom-Kristiansen, T., P.S. Daling, A. Lewis, A.B. Nordvik. 1994. *IFP, WSL and MNS Testing*
Oil Type: Alaska North Slope, Brent Blend, Murban, Bonny Light
Dispersant Type: Corexit 9527 and 9554 and Enersperse 700 on a full range of oil properties and emulsions. Other dispersants were screened using IFP test on 200°C weathered oil
Water Temperature: All tests conducted on ANS at 13 °C
Water Salinity: All tests on ANS at 35 ppt
Presence of Ice: Not studied
Energy Level: Both IFP and MNS tests used on a range of weathered ANS oils. WSL was used on oil residues collected from meso-scale weathering tank. The ANS crude was dispersible until weathered to a viscosity of about 2 to 3000 cP. The MNS test resulted in higher DE estimates than the IFP test. Fifty percent water content emulsions of weathered ANS were dispersed with similar DE as the weathered ANS. Meso-scale (recirculating flume) weathering and dispersant effectiveness tests (using WSL and IFP tests on oil collected from the flume) were also conducted on ANS. After 4 hours of weathering the IFP test estimated 63% effectiveness after 48 hours the WSL test estimated 24% DE on oil that had lost 42% by weight and was a 69% water content emulsion.

Spring, W, T. Nedwed, R. Belore.2006. Icebreaker Enhanced Chemical Dispersion of Oil Spills.
Oil Type: Chayvo Z6, 3 to 12% weathered by weight
Dispersant Type: Corexit 9527. Dispersant applied to oil either prior to energy addition in broken ice or oil on ice tests or after ice breaker had broken ice and exposed the oil for treatment.

Water Temperature: Air temp 0 to -10 °C
Water Salinity: 32 ppt
Presence of Ice: Ice present in 0% to 100% ice sheet. Oil spilled in broken ice, on top of a full ice sheet and under a full ice sheet.
Energy Level: SL Ross wave tank with trolling motor prop wash tests resulted in greater than 90% effectiveness in ice cover ranging from 25% to 90%. With prop wash. Waves only tests with dispersant generated 40 to 56% effectiveness. Low dose (1:110 also effective. Prop wash was effective on oil weathered for 98 hours. In AKER ice basin tests all energy was provided by the prop wash of a scale model azimuthal stern drive icebreaker. Dispersant effectiveness values of between 94% and 97% were measured in the tests. A control test with no dispersant applied resulted in DE of <20 %.Oil drop VMD (d50) of 17 to 45 μm were measured in the tests indicating effective long term dispersion. Oil did not clear the tank after many weeks of sitting with no energy addition indicating long term dispersion even under quiescent conditions.

Venosa, A.D.G.A. Sorial, D.W. King. 2001. Round-robin testing of a new EPA dispersant effectiveness protocol.
Oil Type: Alaskan Prudhoe Bay and South Louisiana crude oil
Dispersant Type: Six dispersants tested, results not tied to specific dispersant
Water Temperature: assumed to be EPA standard temp of 23 ± 3 °C
Water Salinity: synthetic sea water (salinity not reported but assumed to be BF standard of 34 ppt)
Presence of Ice: Not studied.
Energy Level: EPA Baffled Flask. Eight different labs used the Baffled Flask test to determine inter-laboratory variability in testing with this method. It was found that the BF test was much more reproducible and repeatable than the SF test. The effectiveness of the 6 dispersants on fresh Prudhoe Bay crude varied widely from a low of 10% to a high of 89%

Venosa, A., K. Lee, M. Boufadel, Z. Li, E. Wickley-Olsen, T. King, 2008. Dispersant Effectiveness as a Function of Energy Dissipation Rate in an Experimental Wave Tank.
Oil Type: fresh ANS and weathered Mesa
Dispersant Type: Corexit 9500 & Dispersit SPC 1000
Water Temperature: not reported
Water Salinity: not reported
Presence of Ice: Not studied.
Energy Level: EPA /DFO wave tank operated with regular waves, spilling and plunging breakers. Measured energy dissipation rate was similar to field measurements. Both dispersants were effective on the ANS but the Dispersit product required higher energy to achieve same dispersion as Corexit 9500.

White, D.M.; Ask, I.; Behr-Andres, C. 1999. Final Report: Effectiveness Testing for Corexit 9500 on Alaska North Slope Crude Oil in Prince William Sound Seawater at 8°C.
Oil Type: Alaska North Slope crude
Dispersant Type: Corexit 9500. Higher dose rate higher dispersant effectiveness.
Water Temperature: 8 °C.
Water Salinity: PWS sea water (31 to 32 ppt).
Presence of Ice: Not studied.

Energy Level: modified SFT and modified EXDET (no sorbent and same extraction analysis as in SF test). Energy added 0, 12, 24, and 48 hrs after dispersant was applied. Oil was also allowed to ‘weather’ in the test flask between 0, 12, 24, 48, or 72 hours before dispersant application. Highest dispersion occurred with zero weathering and dispersant contact greater than 0. Lowest dispersion occurred with 0 contact time across all weathering. If oil weathers it is less dispersible. If dispersant does not have a chance to mix with oil before energy is applied, poor dispersion.

Wrenn, B., A. Virkus, B. Mukherjee, A. Venosa. 2009. Dispersibility of crude oil in fresh water. Environmental Pollution 157 (2009) 1807-1814.
Oil Type: weathered Mars crude
Dispersant Type: various experimental formulations
Water Temperature: not reported, assumed room temperature and not varied
Water Salinity: All tests conducted using fresh (0 ppt) water. Objective was to develop a dispersant formulation that would provide good effectiveness in fresh water. Objective was met for the single oil tested but authors indicate many other oils would need to be tested to ensure that the dispersant formulation worked over a range of oils
Presence of Ice: Not studied
Energy Level: EXDET test with no variation in energy level.