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Bureau of Safety and Environmental Enforcement (BSEE) Report: BSEE Behavior of Oil on Ice

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Bureau of Safety and Environmental Enforcement

Contract 140E0119F0099

BSEE Behavior of Oil on Ice

Final Report

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1. Background and Objective

BSEE Request for Quotation 140E0119Q0069 for a Task Order against Indefinite Delivery/Indefinite Quantity Contract E17PC00014. Task Order 140E0119F0099, Study the Behavior of Oil on Ice; (Ohmsett Task Order T172-020)

This study is predicated upon the hypothetical scenario for an uncontrolled oil well blowout in the coastal region of the Beaufort Sea along the North Slope of Alaska. Such a blowout could produce a significant crude oil spill affecting coastal lands and waters in proximity with the well. Spill response operations, remedial measures, and fate and transport monitoring would be complicated by the severe weather and ice conditions in the area. This initial study is intended to provide data that would aid in operational spill response planning, equipment staging, spill monitoring, and understanding the impact of such a spill.

Experimental work was conducted at the Ohmsett Facility in New Jersey from early March until early June, 2020. Crude oil was applied to manufactured salt ice blocks at various loadings to simulate a blowout spray plume. A simulated arctic environment for the treated ice blocks was provided by 40-foot and 20-foot transportable (roll-off) refrigerated boxes. Laboratory analyses were conducted at the Ohmsett Laboratory in New Jersey, and at Petroleum Laboratories, Inc. in Houma, Louisiana.

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2. Objective

2.1. Goal

The goal was to obtain quantitative and empirical data to aid in crude oil spill response planning for a specific Alaskan North Slope, off-shore Beaufort Sea oil drilling operation presently under regulatory review. However, much of the specific information associated with this potential drilling site is proprietary. Therefore, a hypothetical blowout scenario was used for this study. Additionally, data and observations from this work were intended for general consumption with regard to similar applications in an offshore arctic environment. Given the broad scope of questions that could need answers in similar operations and the unavailability of specific characteristics and modeling of the drilling operation under review, this study was intended to be an initial and broad approach to the overall objective.

2.2. Assumptions

Experimental assumptions and considerations were:

- Based on an uncontrolled blowout into the arctic air creating an atomized plume at velocities approaching or in excess of 300 m/s.
- A thirty (30) day drilling period for a relief well, thereby resulting in 30 days of uncontrolled release.
- A thirty (30) day period for cleanup; therefore 30 days of spilled oil weathering on ice.
- Simulation of prevailing December-February temperatures of -25°C, and virtual darkness, followed by prevailing March-April temperatures of -15°C, and 20 hours of simulated sunlight.
- The emerging crude oil temperature would be approximately 93° C (200°F). However, the assumption was also made that high velocity flow, and a high degree of atomization would result in virtually instantaneous cooling of the oil to near ambient air temperature prior to landing on the ground or ice.
- Volumetric flow rate of the blowout was not defined.
- Particle size distribution of the blowout plume was not defined.
- Unknown crude oil; therefore, assumed to be similar to Endicott Crude, drilled in the area, at an API gravity of 24 – 27, and a viscosity of approximately 66 cP at 15 C.
- No modifying chemicals were added to the subject crude oil.
- Subject test-ice would be frozen in insulated boxes to replicate thermally frozen polycrystalline ice with vertical crystal structure and brine channels.

This experiment was designed to be as non-intrusive to the ice as possible by using minimal internal instrumentation in the ice matrix.

3. Test Setup

3.1. General Layout

The objective of this study was to determine the level of oil spill cleanup effort required following a well-head blow-out on an artificial island and the surrounding Arctic sea ice. As stated previously, the premise of the study was that the blow-out would be uncontrolled for 30-days, followed by 30-days of oil weathering and recovery. The study was conducted using eight blocks of simulated sea ice using saltwater from the Ohmsett test tank. The saltwater was frozen in one 20-foot and one 40-foot refrigerated roll-off (CONEX) box. Ice blocks were divided into two duplicate groups of four blocks each designated as Group A and Group B. The four blocks within each group would be treated with different oil surface loading designated 1 through 4. These loadings were intended to represent different distances of deposition from the wellhead.

In addition to the ice blocks, two metal pans were placed in the 40-foot CONEX box to act as ice surrogates in order to provide a control for oil application and weathering. These pans were treated with the base rate oil deposition and were exposed to the same environmental conditions as the oil treated ice blocks. The difference was the absence of influence from the ice.
For clarity, Figure 3.1 shows the basic layout of the blocks in the respective CONEX boxes. The access doors are on the left side and refrigeration systems on the right side of the figures.

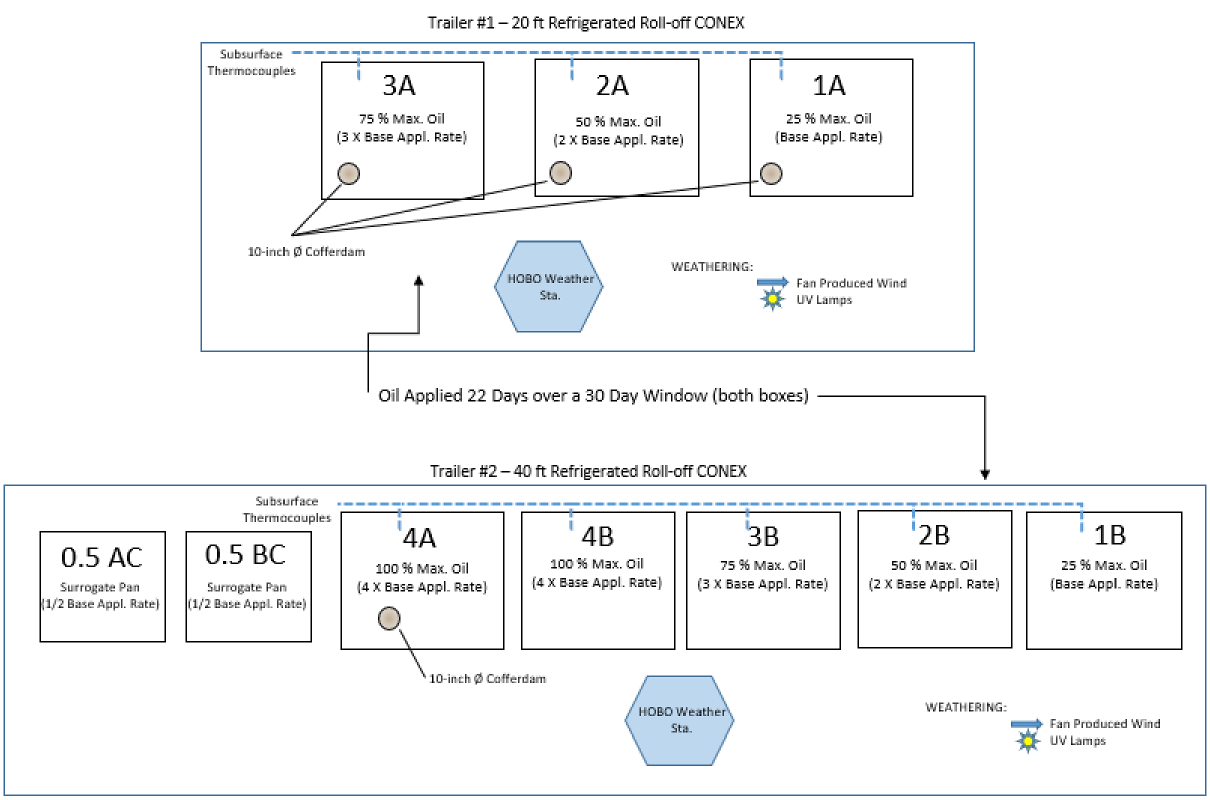

Figure 3.1. Layout of the ice samples and instrumentation in the refrigerated CONEX boxes.

3.2. Ice Formation

To minimize the edge effects of the oil application process and provide ample area to obtain ice cores, the test area for each block was 1m x 1m. To create vertical ice crystal structures and brine channels within the test area, the ice was frozen primarily by thermal cooling of the surface. To minimize lateral ice growth, the sides and bottoms of the ice forms were insulated with 1.5-inch-thick insulation. As the water froze, salt was rejected, and within the closed container the salinity of the remaining solution increased over time. This suppressed ice growth and limited the size of brine channels. To replicate natural ice structures, 20-inch-deep ice forms were used to reduce salinity in the upper part of the salt solution that could affect the brine channels near the ice surface. Lined ice forms were filled with 27-ppt (parts per thousand) seawater from the Ohmsett test tank, and a thermocouple was positioned in the center of the ice to monitor interior temperature as shown in Figure 3.2.

During the freezing process, the ice surface was rough and tended to form a dome. To limit this and to prevent the oil from migrating between the ice and the plastic liner around the edges, a 1m x 1m depression, approximately 1 cm deep with a smooth flat bottom, was machined into the ice block (Figure 3.3). The machining process was completed in the cold to avoid modification of the crystal structure near the surface. As an added precaution to prevent oil migration, a snow berm was built up in the margin between the test area and form.

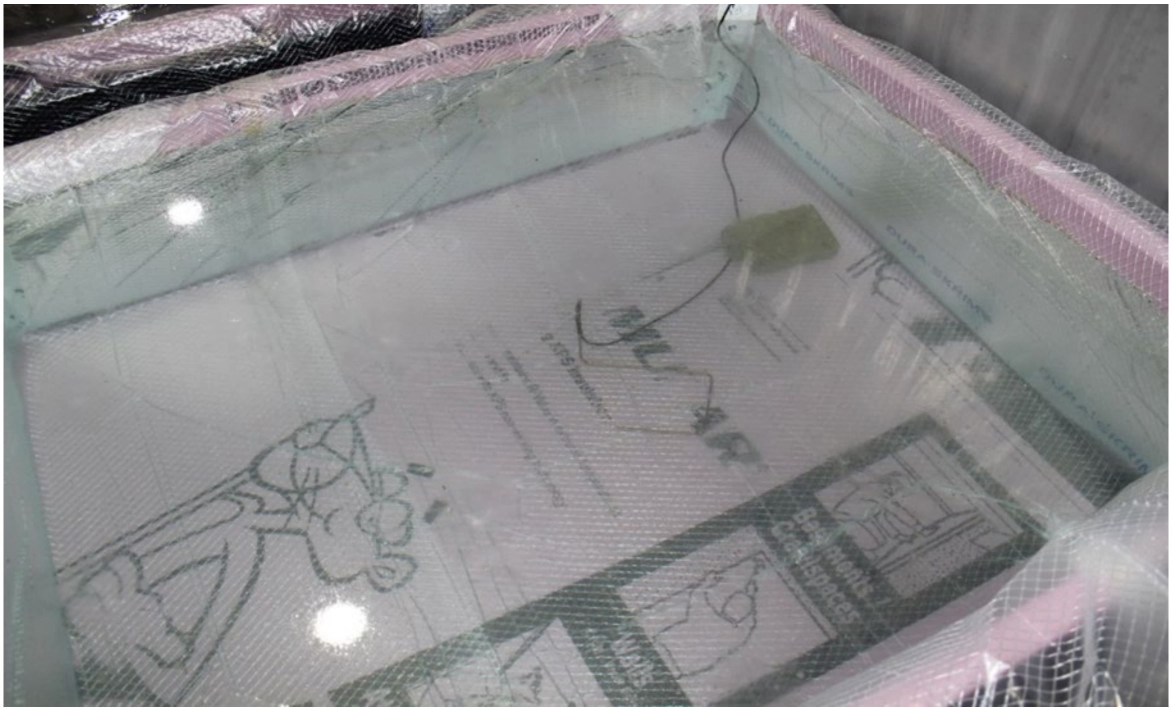

Figure 3.2. Insulated box with plastic liner used as an ice form with a thermocouple to monitor the interior temperature of the ice.

To simulate arctic wind conditions, fans were located in diagonal corners of the respective CONEX boxes (visible in Figure 3.3) to create a circular wind pattern with a nominal wind speed of approximately 4.5 m/s (10 mph). Due to the expected timing of spill response in the current scenario, spring solar radiation was simulated using UV lights that were set to mimic the appropriate diurnal cycle (Figure 3.4). Other instrumentation included thermocouples to measure the temperature of the interior of the ice, air temperature within the CONEX boxes, outside air temperature, a pyrometer to measure solar radiation and reflection to compute the albedo in the 40-foot CONEX box. Albedo is the ratio of the reflected solar radiation to total radiation. Ice has a high ratio as compared to the low reflection/high absorption ratio of a dark surface. Meteorological sensors were monitored by a HOBO® data logger (Onset Computer Corporation) with a 1-minute sample rate.

Figure 3.3. Machining the 1m x1m test area in the 40-foot CONEX box with circulation fans and sensors.

Figure 3.4. Positioning of UV light sources for provide solar irradiation of the ice targets.

4. Experimental

4.1. Subject Test Oil

The impetus for this project is a possible blowout and spill scenario at a new drilling site in the Beaufort Sea near Prudhoe Bay Alaska. At present the site is under review for licensing by BSEE. Planned drilling operations will take place during the winter months, which will afford solid contiguous ice for access to the site and will provide a solid surface to mitigate possible spills. At the time of the study, sample crude oil was not available from the formation in question. However, the assumption was made that Endicott Crude Oil from the same region could act as a surrogate subject test oil. The Endicott Pipeline originates on Endicott's main production island located offshore in the Beaufort Sea, 15 miles east of Prudhoe Bay.

Two small lots of Endicott crude oil were available from the stored inventory at the Ohmsett facility. It was determined that more oil would be needed for the project than either of the lots could accommodate separately. Therefore, the two lots were thoroughly mixed to provide the needed volume and to assure consistent oil properties throughout the project. The basic physical properties of the composite Endicott crude oil were:

- API Gravity = 24.0
- Density @ 20 C = 0.9086 g/ml; density @ 0 C = 0.9235 g/ml
- Viscosity @15 C = 122.6 cP
- Interfacial Tension with Saltwater (30 ppt) = 26.9 dynes/cm
- Water Content < 0.1%

4.2. Loading

In lieu of data related to a blowout plume distribution, or anticipated aerial loading, the literature review of *Guidance on Calculating Blowout Rates and Duration for Use in Environmental Risk Assessment (Norway 2005),* and *Well Specific Oil Discharge Risk Assessment by Dynamic Blowout Simulation Tool (Liu 2016; process Safety and Env. Prot.)*, made it clear that prediction of the nature, flow rate, duration, trajectory, and fluid dynamics of a hypothetical blowout in this study would not be possible. Additionally, attempting to relate the available data to specific oil on ice loading would not be possible. So, a geometric approach was employed whereby dose rates distributed over ice exposure loading was chosen. The approach used multiples of a base loading amount, X, to represent relative distances of aerial deposition from the well head. Four times the application base (4X) represented maximum loading closest to the well. Similarly, loading at 3X and 2X represented distances/volumes in between the maximum and minimum values. The minimum loading, X, represented deposition furthest from the well. In this way, the data could be useful in support of future plume modeling, should data become available.

The Ohmsett facility did not have in its possession a sample of crude oil from the actual well or formation that was the subject of this study. As stated above, Endicott crude oil was chosen as a surrogate because it was assumed to be similar in properties to the subject oil. At the time of this test, the Ohmsett facility had 70 gallons of composite Endicott in its inventory. Therefore, by necessity the base loading referred to above was “backed-out” based on the available Endicott. Further, given the intended use of handheld spray equipment for oil on ice deposition, a base dose was established for a single spray pass over the test ice block area. Greater target loading could then be achieved via multiple passes of this base dose. A brief description of the calculations follows:

Basis:

- Blended Endicott crude oil from the Ohmsett inventory; approximately 32 gallons of "old" Endicott oil with approximately 44 gallons of "new" Endicott, yielding nominally 70 gallons of available subject crude oil.
- Application dose (spray pass) based upon one square meter that was applied in two parallel passes.
- Five (5) dosing variations, with replication:
    - 1A single pass base dose (ice)
    - 2A double pass of base dose (ice)
    - 3A triple pass of base dose (ice)
    - 4A quadruple pass of base dose (ice)
    - 0.5 AC metal pans were half the width of the test area of the ice and only received a half pass (metal surrogate surface for non-ice exposed control)
  - Repeat of above five scenarios as Group B, duplicated.
- Twenty-two (22) weekday single applications (0.5X – 4X) within the 30-day month for each of the 5 replicated variations for the experimental scenario.

Calculated:

1. 70 gal/22 days = 3.18 gal/day

2. (3.18 gal/day) / 2 = 1.59 gal/day (replicate adjustment)

3. Application:

$$.05\ x \cdot appl + x \cdot appl + 2 \cdot appl\ x \cdot appl + 3\ x \cdot appl + 4\ x \cdot appl = 1.59\ gal$$

$$10.5\ x \cdot appl = 1.59\ gal$$

$$x = 0.15\ gal/appl$$

4. Resultant Nominal Coverage Rates:

0.5x = 0.075 gal/half pass ≡ 0.284 L/m^2/half pass

1x = 0.15 gal/m^2 ≡ 0.568 L/m^2

2x = 0.30 gal/m^2 ≡ 1.136 L/m^2

3x = 0.45 gal/m^2 ≡ 1.703 L/m^2

4x = 0.60 gal/m^2 ≡ 2.271 L/m^2

4.3. Oil on Ice Application

Oil was applied manually to target ice blocks using a pressurized paint sprayer equipped with an adjustable spray gun. Paper target spray tests were used to normalize a set of spray parameters such as tank pressure, application pressure at the spray gun, nozzle diameter setting, nozzle distance, and manual spray technique. The result was a reproducible single pass that equated to approximately 0.15 gal/m^2 (0.568 L/m^2). Sequential passes would produce the loading rates as described above. Figure 4.1 shows a paper spray calibration test in progress, while Figure 4.2 shows a spray application of oil to a target ice block.

Figure 4.1. Paper spray application test to establish operational parameters and technique for reproducible loading.

Figure 4.2. Loading metered and timed application of oil to a target ice block.

4.4. Ice

The motivation for the investigation was to determine the level of effort required to clean up an ice borne oil spill and determine if the oil would migrate into brine channels, thereby complicating recovery efforts. The experience of one of the participants in the 2012 International Association of Oil and Gas Producers Arctic Oil Spill Response Joint Industry Project (IOGP Arctic JIP)evaluation of sensors provided useful information for this study. The objective of the IOGP study was to evaluate various subsea, surface, and aerial sensors for detecting oil under and in the ice as it became encapsulated and migrated up the brine channels to the surface. To document the microstructure of sea ice, core cross sections were analyzed using a micro-CT scanner (Courville 2017). During the IOGP study, submerged oil migrated up the brine channels due to a combination of the buoyancy of the oil and capillary action within the brine channels. For this study, with the oil on the surface, buoyancy is negated and any oil migration into the ice would be due to capillary action and gravity. To document the migration, ice was periodically cored during both the application and weathering phases of the program. To minimize the impact of the cores on the ice, small ice cores, 1-cm in diameter, were obtained using an ice climbing anchor (Figure 4.3). The experimental plan initially included the use of short lengths of heated pipe to be set on the ice to isolate the sampling area from the surrounding oil. This approach was abandoned when it was observed that the oil was viscous enough to hold a square edge during the coring process (Figure 4.3). During the coring process, the top 2- 3mm of the ice was pulverized; however, the recovered ice and hole in the ice provided a window to examine a narrow cross section. The dates and respective ice samples for the Small Cores (SC) are listed in Table 4.1 and 4.2.

Figure 4.3. SC from sample 4A prior to tenth oil application.

Following the oil application phase, Large Cores (LC), 7.5 cm in diameter, were obtained from the A ice blocks (Figure 4.4). The larger diameter core had multiple ice crystals and brine channels with better representation of the ice structure.

Figure 4.4. Obtaining a 7.5 cm large core from sample 1A.Table 4.1. Oil Application, Ice Coring and Daylight Schedule

Table 4.1. Ice Coring and Daylight Schedule as Oil was Applied

Test Day	Date			1A	2A	3A	4A	1B	2B	3B	4B	LTs
1	Wed	3/4/2020	X									12
2	Thu	3/5/2020	X								SC	12
3	Fri	3/6/2020	X									12
4	Sat	3/7/2020										12
5	Sun	3/8/2020										12
6	Mon	3/9/2020	X									12
7	Tue	3/10/2020	X				SC					12
8	Wed	3/11/2020	X									12
9	Thu	3/12/2020	X									12
10	Fri	3/13/2020	X									12
11	Sat	3/14/2020										12
12	Sun	3/15/2020										12
13	Mon	3/16/2020	X									12
14	Tue	3/17/2020	X			SC						12
15	Wed	3/18/2020	X									12
16	Thu	3/19/2020	X									12
17	Fri	3/20/2020	X									12
18	Sat	3/21/2020										12
19	Sun	3/22/2020										12
20	Mon	3/23/2020	X									12
21	Tue	3/24/2020	X							SC		12
22	Wed	3/25/2020	X									12
23	Thu	3/26/2020	X									12
24	Fri	3/27/2020	X									12
25	Sat	3/28/2020										12
26	Sun	3/29/2020										12
27	Mon	3/30/2020	X				SC					14
28	Tue	3/31/2020	X									14
29	Wed	4/1/2020	X									14
30	Thu	4/2/2020										14

Key
SC – Small ice core after surface scrape for oil sample.
LC – Large ice cores, 3-inch diameter.
XS – Cross Section of Ice.
LTs- Hours UV lights on

Table 4.2. Ice Coring and Daylight Schedule as Oil Weathered

Test Day	Date		1A	2A	3A	4A	1B	2B	3B	4B	LTs
1	Fri	4/3/2020	LC	LC	LC	LC					14
2	Sat	4/4/2020									14
3	Sun	4/5/2020									14
4	Mon	4/6/2020									14
5	Tue	4/7/2020									14
6	Wed	4/8/2020								SC	14
7	Thu	4/9/2020									14
8	Fri	4/10/2020									14
9	Sat	4/11/2020									14
10	Sun	4/12/2020									14
11	Mon	4/13/2020									14
12	Tue	4/14/2020									14
13	Wed	4/15/2020				SC					14
14	Thu	4/16/2020									14
15	Fri	4/17/2020									14
16	Sat	4/18/2020									14
17	Sun	4/19/2020									14
18	Mon	4/20/2020									14
19	Tue	4/21/2020									14
20	Wed	4/22/2020									14
21	Thu	4/23/2020									14
22	Fri	4/24/2020								SC	14
23	Sat	4/25/2020									16
24	Sun	4/26/2020									16
25	Mon	4/27/2020									16
26	Tue	4/28/2020									16
27	Wed	4/29/2020									16
28	Thu	4/30/2020				SC					16
29	Fri	5/1/2020									16
30	Sat	5/2/2020									16
31	Sun	5/3/2020									16
32	Mon	5/4/2020									16
33	Tue	5/5/2020	XS	XS	XS	XS	XS	XS			16
34	Wed	5/6/2020									16
35	Thu	5/7/2020									16
36	Fri	5/8/2020									16
37	Sat	5/9/2020									16
38	Sun	5/10/2020									16
39	Mon	5/11/2020									16
40	Tue	5/12/2020							LC	LC	16
41	Wed	5/13/2020									16
42	Thu	5/14/2020									16
43	Fri	5/15/2020									16
44	Sat	5/16/2020									16
45	Sun	5/17/2020									16
46	Mon	5/18/2020									16
47	Tue	5/19/2020									16
48	Wed	5/20/2020									16
49	Thu	5/21/2020									16
50	Fri	5/22/2020									16
51	Sat	5/23/2020									16
52	Sun	5/24/2020									16
53	Mon	5/25/2020									16
54	Tue	5/26/2020									16
55	Wed	5/27/2020									16
56	Thu	5/28/2020									16
57	Fri	5/29/2020									16
58	Sat	5/30/2020									16
59	Sun	5/31/2020									16
60	Mon	6/1/2020							XS	XS	16

Key

SC – Small ice core after surface scrape for oil sample.

LC – Large ice cores, 3-inch diameter.

XS – Cross Section of Ice.

LTs- Hours UV lights on

Figures 4.5, 4.6, 4.7 and 4.8 show images of the cross sections of ice cores after the application phase from blocks 1A, 2A, 3A and 4A respectively. Oil migrated into the upper brine channel in sample 2A and slightly into 4A. Oil on the A samples was allowed to continue to weather for 30 days to provide a duplicate for the B samples.

Figure 4.5. Cross section of large ice core from 1A following the application phase.

Figure 4.6. Cross section of large ice core from 2A following the application phase.

Figure 4.7. Cross section of large ice core from 3A following the application phase.

Figure 4.8. Cross section of large ice core from 4A following the application phase.

At the completion of the 30-days of weathering, two perpendicular vertical ice slabs were cut from all the samples using a chainsaw, except for 3B and 4B which were reserved for further weathering. The slabs for the A samples are shown in Figures 4.9, 4.10, 4.11 and 4.12 respectively, and slabs from 1B and 2B are shown in Figures 4.13 and 4.14.

Figure 4.9. Cross section slab of ice from 1A with the skeleton layer at the top of the photo and the ice surface on the bottom. There is no evidence of oil migration after 33 days of weathering.

Figure 4.10. Upper layer of ice from 2A showing oil migration following 33 days of weathering.

Figure 4.11. Upper layer of ice from 3A with slight oil migration following 33 days of weathering.

Figure 4.12. Cross section slab of ice from 4A with the ice surface on the bottom of the photo showing slight oil penetration following 33 days of weathering.

Figure 4.13. Cross section slab of ice from 1B with the ice surface at the top of the photo with slight oil migration.

Figure 4.14. Cross section slab of 2B with oil migration following 30 days of weathering.

Once the destructive sampling of the six blocks was complete, the ice blocks were removed from the refrigeration units and relocated to the north end of the Ohmsett tank to melt and determine the volume of oil in the brine channels. Ice samples 3B and 4B were relocated to the 20-foot refrigerated CONEX for continued evaluation of the effect of UV light on the weathering process. The transfer was done as quickly as possible to minimize the exposure to outside ambient conditions.

To monitor the oil migration in 3B and 4B samples, large cores were obtained 40 days after the weathering process started. The cross sections are shown in Figures 4.15 and 4.16 respectively. Following 60 days of weathering, the cross sections were cut using a chainsaw from 3B and 4B as shown in Figure 4.17 and 4.18.

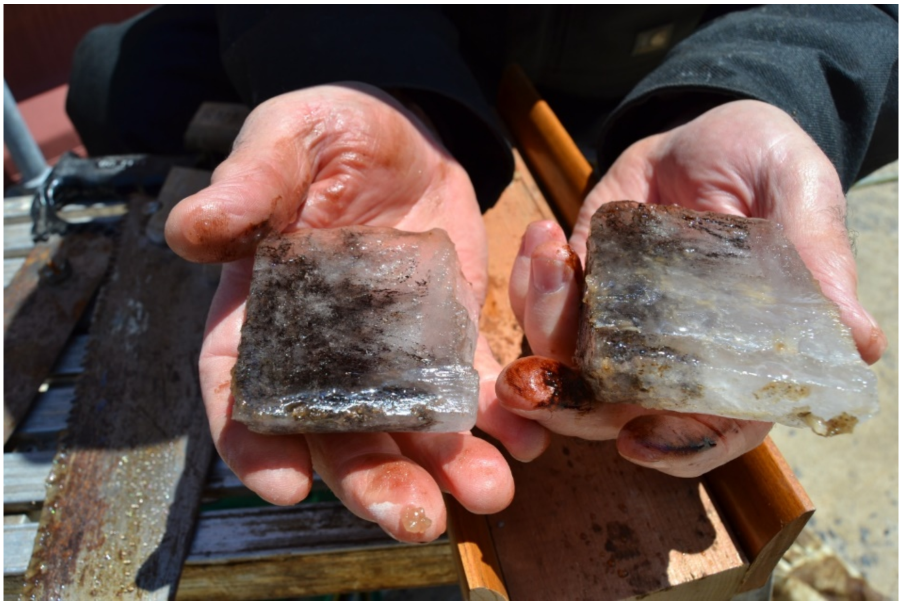

Figure 4.15. Cross section of large ice core from 3B after 40 days of weathering.

Figure 4.16. Cross section of large ice core from 4B after 40 days of weathering.

Figure 4.17. Cross section slab of 3B with oil migration following 60 days of weathering.

Figure 4.18. Cross section slab of 4B with oil migration following 60 days of weathering.

The Arctic daylight was simulated using UV lights; the number of hours per day is listed in the coring schedule in Table 4.1 and in Table 4.2 in the column titled LTs.

To validate the salinity gradient, several of the ice cross sections were cut horizontally, melted, and the salinity determined. As anticipated, the salinity increased with ice depth, and the salinity of the brine solution in the center of the ice sample was high enough to prevent freezing. This is discussed further in Section 5.3.

4.5. Analytical

During oil application and the subsequent weathering period, analyses performed in the Ohmsett facility laboratory on ice cores, oiled ice cores and sections, and oil scrapings were:

BSEE Oil on Ice Analytical Protocol for Cores:

- Small and Large (3 inch) Cores
    - Melted Water
        - Photo and Observations (oil)*
        - Salinity by Refractive Index
        - Mass (Total – Core Weight)
        - Density (Densitometer)
    - Surface Oil (Scraped)
        - Water Content (Centrifuge)
        - Viscosity
            - @ -17.8 C
            - @ 15 C
        - Density
            - @ 0 C
            - @ 5 C
            - @ 10 C
            - @ 15 C
            - @ 20 C
        - IFT vs Tank Water Adjusted to 32 ppt Salinity

* In the case of Large Cores, the volume of separated oil was also measured.

A schedule of ice core and oil sampling is listed in Table 4.1 and 4.2.

Oil samples were also sent to Petroleum Laboratories, Inc. in Houma, Louisiana for SARA (saturates, aromatics, resins, and asphaltenes) analysis via ASTM Method D2007. The oil samples selected for SARA analysis were thin oil layer (base loading) 30-day samples, and 60-day samples; and thick oil layer (maximum loading) 30-day, 60-day, and 90-day samples.

5. Results

5.1. Ice

The objective of this study was to identify the type of equipment required to recover oil from the surface and, if necessary, the upper layers of ice. The experiment was designed to be wide in scope to identify the variables controlling the interaction between oil and ice, migration and weathering of the oil, and the type of equipment necessary for cleanup. Considering the lack of previous work for this type of physical modeling, assumptions were made regarding the application and weathering processes in order to identify controlling variables. The ice blocks used for this mesoscale modeling were large enough to ignore the edge effects during the freezing process, and the end of the oil application spray patterns when sampling the ice. As the seawater froze, salt was rejected into the solution thereby depressing the freezing point and suppressing the freezing process. The slowed freezing rate allows for the formation of larger ice crystals. The ice blocks were deep enough to reduce the salinity gradient near the surface, however it was realized that increasing the brine within the ice crystals would enhance oil migration into the ice. In retrospect saltwater with a lower salinity could have been used for the experiment since only a fraction of the salt is trapped in the ice. A larger tank with a larger volume of water would:

- Minimize the increase in salinity of the liquid as the salt was injected.
- Allow the liquid under the ice to be circulated and the salinity to be controlled.

In the case of this initial study the use of a larger tank was considered to be too complex as the focus was the ice-oil interface.

Although the technicians wore personnel protection equipment (PPE) while spraying the oil, there was a concern for oxygen depletion; therefore, the door of the refrigerated container was left open while spraying oil. Strips of vinyl were used as a thermal curtain inside the door to minimize heat loss, however blocks 4A and 3B that were near the door may have experienced a thermal gradient in the short time required to spray the oil. The thermocouples frozen into center of all the ice block were stable during the test even during oil application. Surface temperature of the blocks was measured before and after the oil was applied using a handheld infrared thermometer. The statistics of the temperature reading for the respective blocks are listed in Appendix A; and the oil application times, weight of the oil applied, and calculated application rates are listed in Appendix B for each of the blocks. Given the manual application of oil, the standard deviation of the oil application rate is small, and it can be reasonably assumed that each oil application was uniform in thickness.

Solar radiation was simulated with a series of UV lights mounted about 1.5 m above the ice and cycled daily to replicate the arctic spring (Table 4.1 and 4.2). Although the UV source had visible spectral components, in retrospect a more complete spectrum with IR wavelengths should have been included as a better representation of the spring sun in Alaska.

Given the limitations of the experiment, the observations provided valuable information on the weathering process, in addition to raising some interesting questions. During the oil application phase when the ice was scraped for coring, there was no discoloration of the ice which indicated there was no oil migration. This was verified with the small cores and inspection of the bore hole at the conclusion of the application phase. Large cores were recovered from the A samples. Only 2A had evidence of oil migration into the brine channels. Following the weathering phase, perpendicular cross-sections were cut from the A ice blocks, as well as blocks 1B and 2B and the following observations were made:

- Although the replicate 2 blocks were in a corresponding location in a different refrigerated CONEX (Figure 3.1), they were the only blocks with oil penetration.
- Based on the observation of the Series A blocks, it was assumed that Blocks 3B and 4B did not have any oil migration when the blocks were moved to the smaller refrigerated CONEX.
- The large cores obtained from blocks 3B and 4B seven days after being relocated had oil in the brine channel. Cross-sections cut from the blocks 27 days after they were relocated had significant oil in the brine channels.

These observations lead to several considerations of what could have been different. To mitigate potential variations:

- Block relocation was performed as quickly as possible in order to limit exposure to ambient temperatures and effects.
- The ambient temperatures within the boxes were kept within the operating parameters of the refrigeration units.

However, the combination of the move between refrigeration units and any cumulative effects of the UV hours at 16-hours per day may have facilitated oil mobility.

Several hypotheses have been formulated to explain the observed oil migration into the ice. The application process was discrete and conducted early in the morning on application days using oil at ambient temperature.

Replicates 3 and 4 had three and four passes per application respectively. As the oil layer built up, the cold thick layer of oil would be less responsive to the warm oil being applied. In effect the thick layer insulated the ice.

- The thin layer on the replicates numbered 1 may respond to the added warm oil, but quickly lose the thermal momentum due to the cold temperature.
- In the case of Replicates 2, the combination of the warm oil and UV light may have provided enough energy for penetration.

That being said, there is some question with respect to the oil penetration into blocks 3B and 4B after 33-days of weathering. Although the ice temperature was stable, the brine may have drained, thus drawing the oil into the voids within the brine channels. To develop a better understanding of this unexpected phenomenon there is an impetus for future research on this process.

5.2. Oil

Given the limited quantity of oil, the method for sampling, and the need to examine a number of unknown interactions, there were a great number of small individual samples, but few opportunities to establish trends. The best opportunity for simple trend analyses was to look at the 4A and 4B samples. These provided the highest number of oil samples over the greatest length of weathering time, and the maximum volume of oil per sample. For these samples, we looked at density vs time (with and without correlation to water content), viscosity vs time (with and without correlation to water content), and interfacial tension vs time.

5.2.1 Density

The changes in **density** may be summarized as follows (Figures 5.1, 5.2 and 5.3):

- As anticipated, density at a particular temperature increased over time with weathering due to the loss of volatile components of the crude oil. Similarly, the density was greater for samples of the same degree of weathering but at lower temperature. However, density changes of any one oil exposure ranged from <0.1 % to 1.4 %. The corresponding loss of volatiles does not match that of fresh Endicott in a typical weathering exercise over time. The difference can probably be ascribed to the low temperatures and slower evaporative processes associated with the overall weathering environment.
- Generally, densities increased with increasing water content in addition to increased time of weathering. This phenomenon would also be anticipated. However, at this time it is difficult to discern the relative contribution water content would have as opposed to time weathering.
- The data for water content in general was somewhat noisy, or variable. This may be attributable to the fact that oil samples taken from an oil slick on ice are scraped for collection. This would certainly increase the probability for inclusion of excess water from the underlying ice surface that would not otherwise have been part of the sample.
- Another complication associated with water content in an oil sample, whether introduced by sampling technique or not, is the fact that the laboratory constant temperature densitometer starts to exhibit operational error at temperatures below the freezing point of the water which results from a loss of homogeneity in the sample. This is especially complicated by the fact that surface ice adjacent to the oil would normally be depleted in salt thereby exhibiting a tendency for higher freezing points.

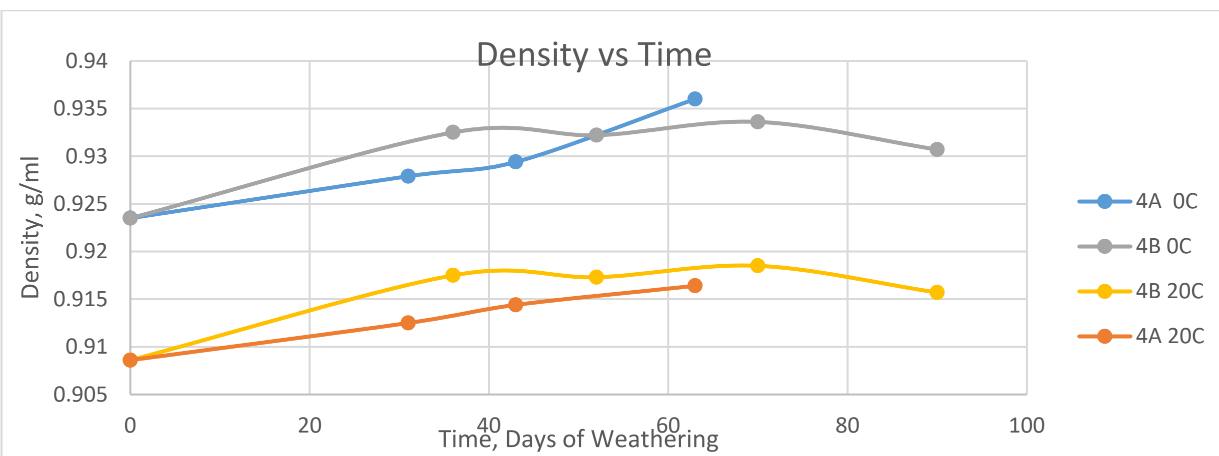

Figure 5.1 Change in Density over Time

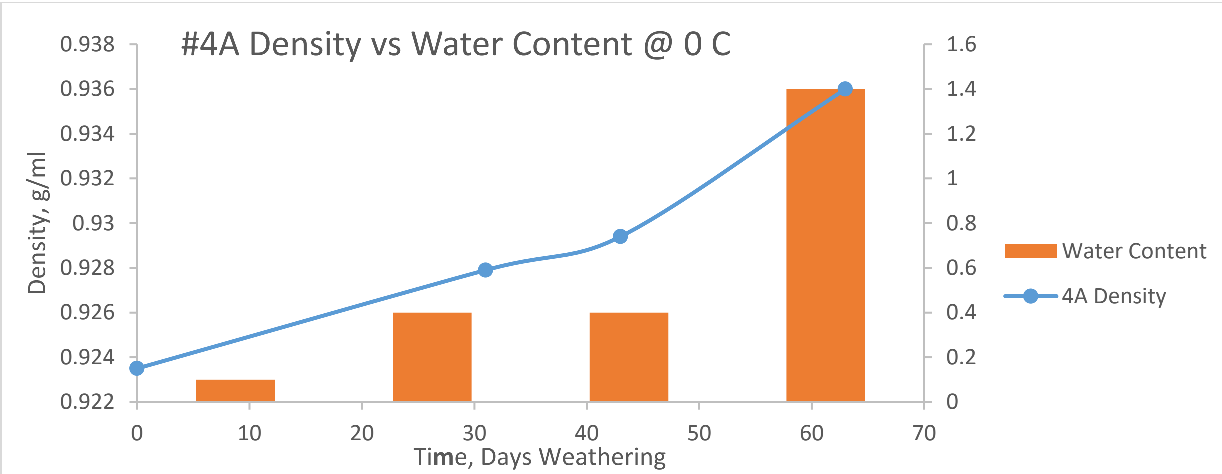

Figure 5.2 Block 4A Change in Density in Relation to Water Content

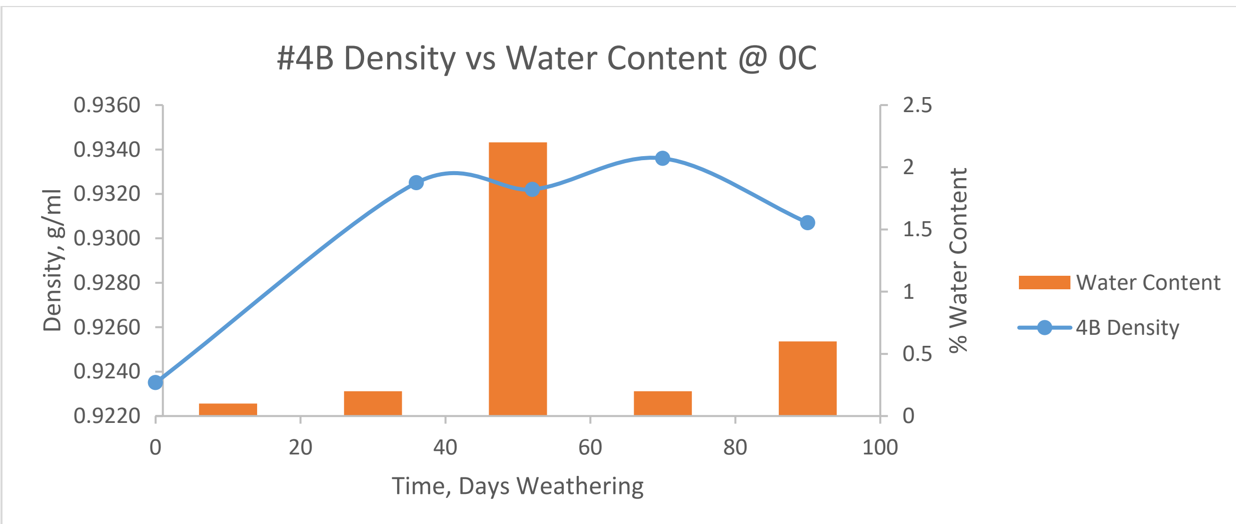

Figure 5.3 Block 4B Change in Density in Relation to Water Content

5.2.2 Viscosity

A look at 4A and 4B data for **viscosity** indicates (Figures 5.4, 5.5, 5.6, 5.7):

- At 15 C, the general trend for viscosity is to increase with time. The greatest increase was approximately 59% for an intermediate point with 4B, and 30% for 4A. This is what could be considered a general trend. However, review of the data indicates a fair amount of variability. Again, the presence of water as an artifact of surface sampling could account for this.
- At -17.8 C, the variability was much greater with initial and final values in time being similar. This is not surprising given water from sampling would become crystallized, and the presence of these solids in the viscometer cup and spindle would cause great variability.
- Review of water content did not correlate well with any viscosity trend. However, it did indicate the possibility for great variability in the viscosity data.

- Note that initial data for viscosity is based upon that of initial fresh Endicott crude oil.

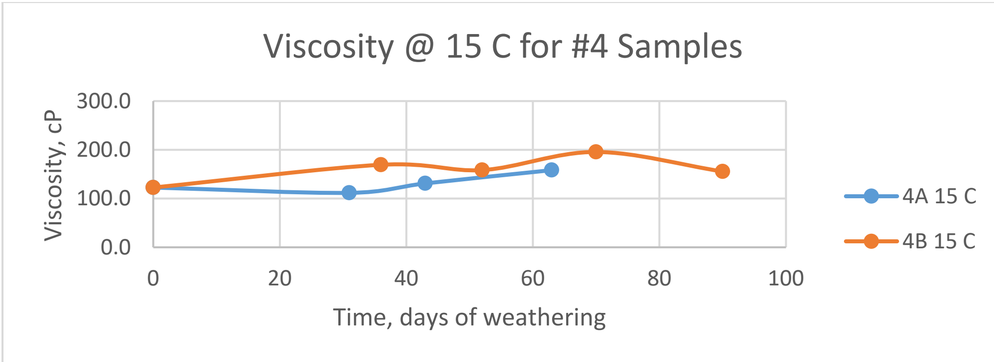

Figure 5.4 Replicates 4 Viscosity Change of Time at 15 ^{o}C

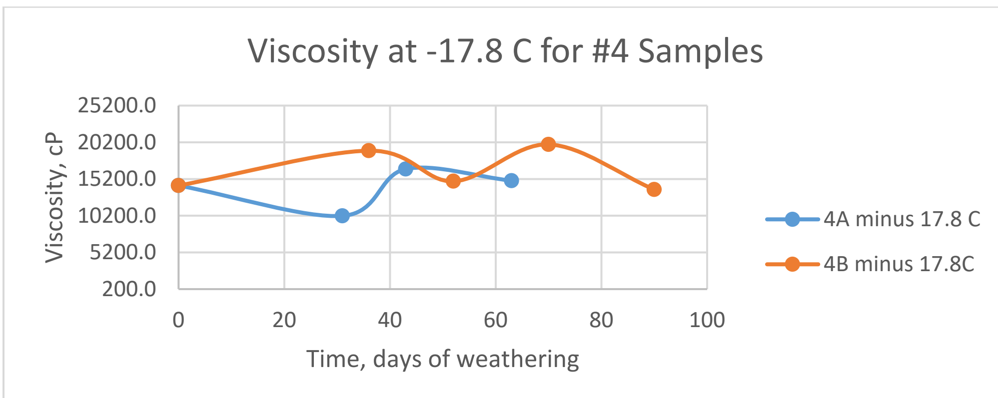

Figure 5.5 Replicates 4 Viscosity Change of Time at -17.8 ^{o}C

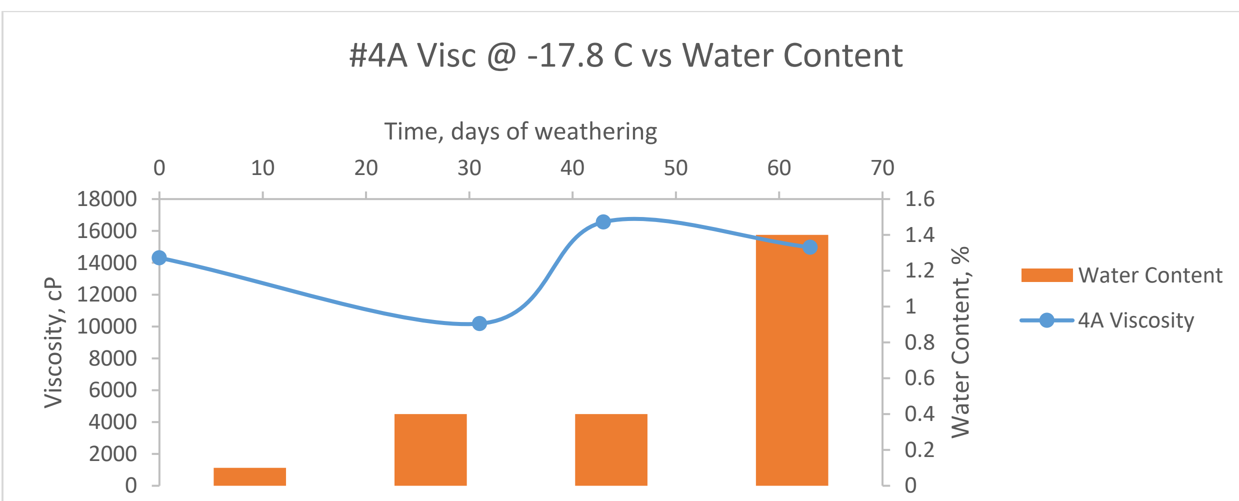

Figure 5.6 Block 4A Viscosity vs Water Content at -17.8^{o}C

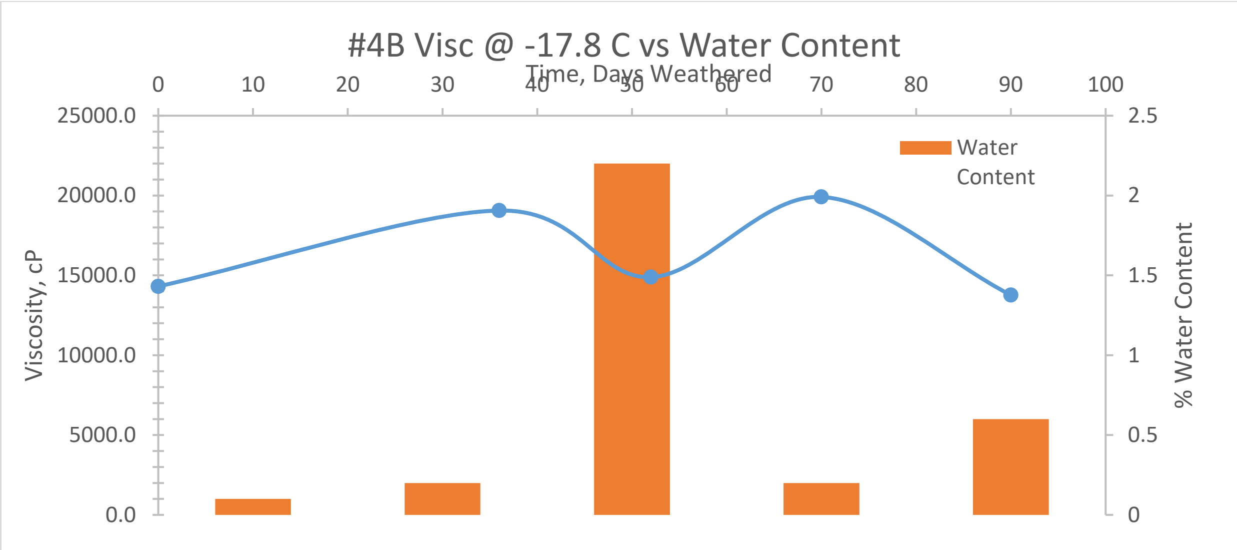

Figure 5.7 Block 4B Viscosity vs Water Content at -17.8 ^{o}C

5.2.3 Interfacial Tension (Figures 5.8, 5.9 and 5.10)

Interfacial tension (IFT) is the force of attraction between the molecules at the interface of two immiscible fluids. This force arises because of the free energy developed when a contiguous fluid experiences the imbalanced interactions at a fluid boundary. Unlike viscosity and density, which show systematic variations with temperature and degree of evaporation, IFT of liquid petroleum products do not show trending correlations. The attached data and Figures 5.8, 5.9, and 5.10 confirm this with respect to replicates 4. There seems to be very little correlation between IFT changes verses time of weathering or water content.

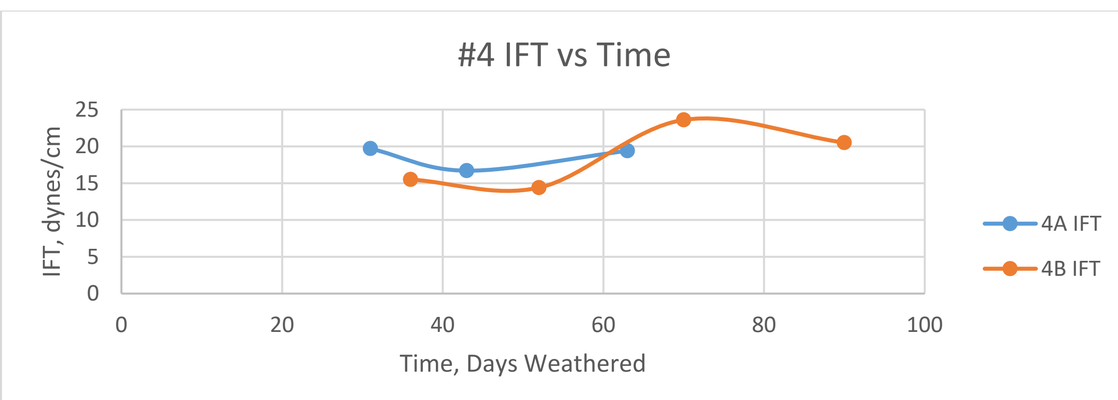

Figure 5.8 Replicates 4 IFT Changes over Time

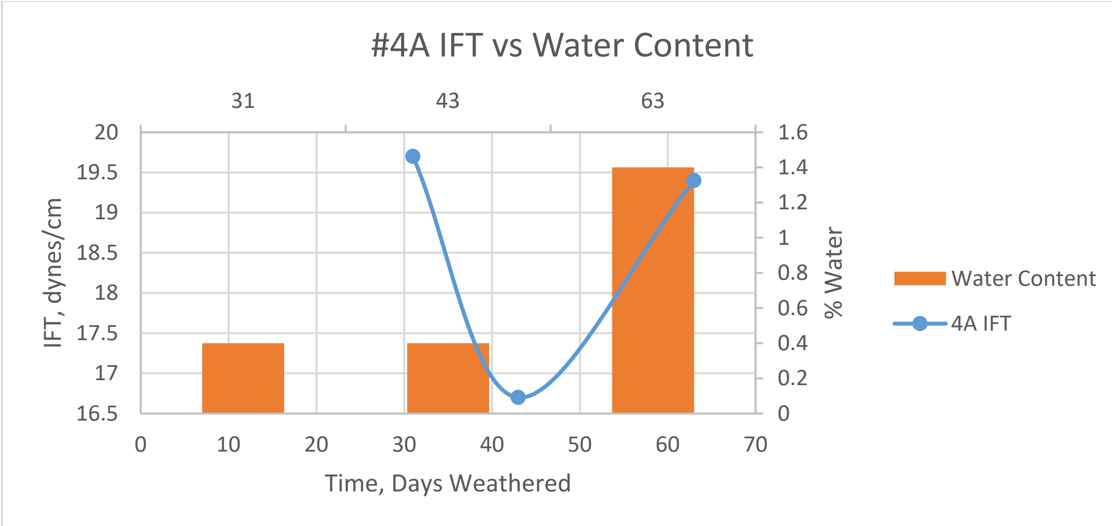

Figure 5.9 Block 4A IFT vs Water Content

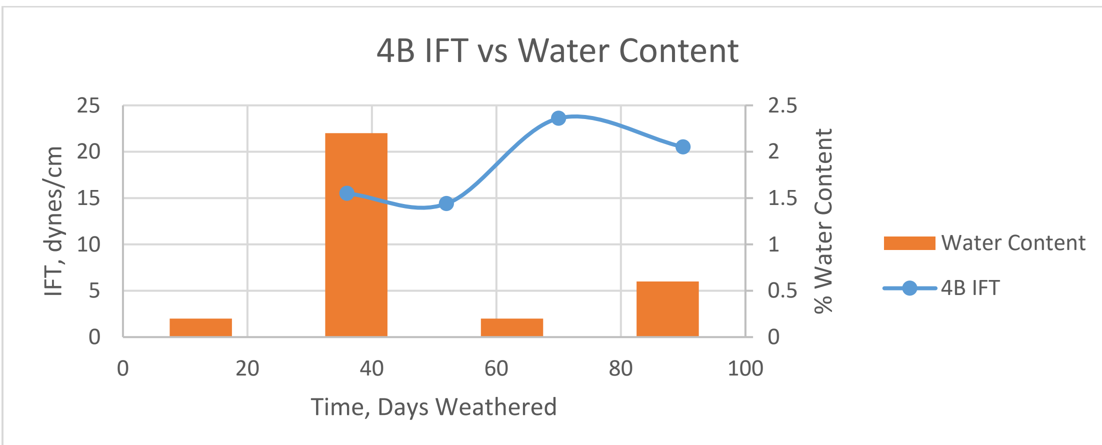

Figure 5.10 Block 4B IFT vs Water Content

5.3. Water

As saltwater freezes, the water tends to freeze in its pure form, and the salt becomes excluded from the water crystal matrix of the skeletal layer i.e., freezing front. As the water between the adjacent ice crystals freezes, brine trapped between the boundaries of the ice crystals create brine channels. Cross-section of the brine channels are in equilibrium between the temperature of the ice and the freezing point of the trapped brine. With an increase in the temperature of the ice, the brine channels expand. The converse is true as the ice cools. The resulting structures known as brine channels contribute to structural, electrochemical, transport, and friable characteristics of the ice and spilled oil system. Review of the analytical data associated with water from the oil and ice systems generally indicates that water collected high in the ice structure was lower in salinity than water collected lower in the same structure. The starting saltwater was analyzed at 30 parts per thousand (ppt). The next several samples, which were melted ice samples from shallow borings, averaged less than 8 ppt. The highest salinity was found to be

200 ppt (sample FA099-27a), a bottom sample. All water samples correlated as expected with regard to conductivity and density. Water data were determined in the laboratory at temperatures in the range of 18.4 to 21.9 C, except for density data which were determined in a constant temperature densitometer at 20 C.

5.4. SARA Analysis

SARA analyses were performed on key samples of collected oil as indicated below (Table 5.1). The significance of this data is addressed in Section 6.0, Conclusions and Discussion.

Table 5.1 Comparison of SARA Analysis

SARA Analytical Results									
Sample	**API**	**Flash Point, F**	**Paraffin, wt. %**	**Pour Point, F**	**Sulfur, wt. %**	**Saturates, wt. %**	**Aromatic, wt. %**	**Asphaltene, wt %**	**Resins, wt. %**
FA099-00 Subject Oil	24.2	88	0.96	46.4	1.3772	34.24	49.92	0.36	15.48
FA099-06 1A-30 Day	21.4	107	0.83	60.8	1.4484	36.42	46.77	2.30	14.50
FA099-28 1B-60 Day	21.6	135	1.01	60.8	1.3960	33.45	49.63	2.24	14.67
FA099-05 4A-30 Day	23.0	83	0.37	59.0	1.4034	35.34	49.57	2.09	12.99
FA099-14 4B-60 Day	22.5	78	1.16	59.0	1.3612	39.68	44.25	2.29	13.78
FA099-20 4B-90 Day	23.1	80	0.65	51.8	1.3727	34.51	49.52	1.04	14.93

6. Conclusion and Discussion

This section focuses on ice structure and ice influence on oil; water and its influence on ice formation and on deposited oil; and on the oil itself. Discussions will place emphasis on operational concerns associated with spill response in the defined arctic environment.

6.1. Oil and Ice

The Endicott crude oil used in this study was a surrogate for the actual oil that will eventually be pumped from the subject formation. This was because no actual oil sample was available at the time of this study. Despite this, a number of conclusions and relevant estimates may be drawn from the data and observations of this bench scale study.

As stated previously, it was assumed that a well blowout would result in oil ejected at approximately 300 m/s, at a temperature of 93^{o}C, and into a prevailing air temperature of -23^{o}C. This form of explosive release would probably result in immediate atomization of the oil accompanied by an abrupt drop in pressure and temperature due to the high exit velocity. Initial volatilization of light ends in the oil would occur but would probably be limited as the oil spread and quickly approached atmospheric temperature. Upon hitting the ground, a distributed slick will form with heavier oil droplets depositing closer to the well, and lighter droplets carrying further from the well before depositing. Very light mists and vapor would be transported further with wind (Liu, 2016). The slick would tend to extend in a plume in the prevailing direction of the wind. Once on the frozen ground (ice and snow), the slick would be largely immobilized. The oil would cool to the temperature of the ground cover and would probably not change significantly in temperature dependent properties. This would especially be true where oil could collect in thicker layers. This would result in reduction of surface exposure and further reduction in volatilization. Results from this study tended to support this given the maximum change in density under any of the treatment scenarios was no more than a few percent. It must be noted that the test method used to apply oil to ice blocks employed a pre-weighed, pressurized tank and hand-held nozzle system. Oil ejection, atomization, transport, and deposition will no doubt be quite different in an actual spill at scale.

Collected oil sample data indicate that the viscosity increases with lower temperatures as expected. However, the presence of included water also produced higher viscosities. Generally speaking, the longer the oil is exposed to the environment, the colder the temperature, and the greater the mass of water in the oil matrix, the greater the viscosity. However, it was difficult to establish definitive trends with the present data set given the high variability in water mass. This variability was most likely associated some combination of the need to perform scrape sampling, the varied exposure of the oil layer to the ice, and temperature variations associated with working in separate, small volume “roll-off” refrigerated boxes.

Unlike viscosity and density, IFT of liquid petroleum products does not show trending correlations. Further, the relationship between saltwater, salt ice, and crude oil is not well established (Faksness, 2008). In many cases it seems that changes in salinity will impact IFT with crude oil, but only minimally. Review of the data indicates there to be very little correlation to IFT changes verses time of oil weathering or water content for this crude oil under these test conditions.

SARA data for the chosen samples is largely in line with the above findings. Oil spraying and deposition, plus time of exposure to air and ice is accompanied by a general increase in API gravity. However, that increase is minimal, with the greatest increase being approximately 2%. Flash point was observed to increase slightly in the thinly deposited samples, though the cause of this is unknown. However, the change in flash point was not significant overall. There was an overall increase in pour point from approximately 12 to 31 % with the greatest increase again in the thinly deposited oil slicks. This result was expected given the increase in viscosity that was recorded. Weight percent in sulfur, saturates, aromatics, and resins did not change significantly with exposure of the crude oil when compared to the initial crude oil sample. There were significant increases in asphaltene weight percent from the initial crude, although this is reasonable given the very low volatility, higher polarity, and low relative concentration of this broad grouping of compounds.

6.2. Water

As stated previously, water tends to freeze in its pure form, i.e., as saltwater freezes salt is excluded from the water crystal matrix. This creates collection points for salt crystals (vacuoles) within the freezing front, or skeleton layer, on the bottom of the ice (Courville, 2017). As the ice thickens, brine channels form within the ice structure and contribute to the structural, electrochemical, transport, and friable characteristics of the ice/spilled oil system. Analytical data associated with water from the ice/oil systems indicate that water collected high in the ice structure was lower in salinity than that collected lower in the same structure. While the starting saltwater had a salt concentration of 30 parts per thousand (ppt), results from melted ice samples from shallow borings averaged less than 8 ppt salinity. The highest salinity was found to be 200 ppt from a bottom sample (sample FA099-27a). All water samples correlated as expected with conductivity and density data.

6.3. Ice

In general, the cold layers of oil on the ice were of high enough viscosity that there was no horizontal spread to areas that were cleared for ice coring. Additionally, there was no evidence of oil migrating into the ice during the application phase, based on the scraped ice and small ice core samples. At the conclusion of the application phase:

- Only block 2A, with two passes per application, had any penetration into the ice, i.e., there was no penetration into Block 1A with the single pass per application or Blocks 3A and 4A with the multiples passes per application.
    - This observation was reinforced with the cross-sections recovered after 33-days of weathering where only 2A and 2B were observed to have oil in the brine channels.
- Following an additional seven days (total= 40 days) of weathering, oil migrated into Blocks 3B and 4B.
    - Deep penetration was observed after sixty days of weathering.

There is insufficient data to definitively identify the migration processes, e.g., related to changes in the oil properties, effects of UV exposure and replacement of brine as it drained from brine channels. Although these actual processes are of interest, the goal of the described research project was to identify equipment and potential real-world processes required for spill response.

6.4. Discussions for the Field

This study was intended to produce data and observations that could provide insight to aid in response preparations. Indications from this surrogate study lead to the following considerations that should prove informative in the field.

- The oil will probably deposit in a pattern extending from the well in the direction of the prevailing wind. It would be expected that heavier oil deposition on the surface would be closer to the well, thinner deposition would be further.
- Some volatilization of light ends will likely occur, but once the oil contacts the frozen ground that process would be slowed. Our study indicates that oil properties would not change significantly once on the ground, especially in thicker depositions.
- Oil penetration into the ice will be dependent upon time of exposure, temperature history, and thickness of the deposited slick, exposure to sunlight, and the presence and nature of brine channels in the ice.
- Equipment should be available to scrape the oil, which will likely be more viscous and possibly sticky, from the periphery of the deposition toward the well. Every effort should be made to limit the amount of ice and water scraped up with the oil.
- Since total exclusion of water will not be possible, and given the prevalence of Arctic temperatures, recovered fluids will likely be highly viscous and dense. Included water will exacerbate this condition, especially if water-in-oil emulsions form with handling and transport.
- If the decision is to collect as much oil as possible, equipment will be needed for melting ice, heating the oil, and decanting.
- As an alternative, surface oil may be scraped into large piles, most likely mixed with ice, into large piles that could support burning. (API ISB 2016)
- Oil residue on the ice surface will decrease the albedo and increase the in solar absorption will change the engineering properties of the ice. With recovery equipment working on the ice, responders need to be aware of the potential for the loss of load-bearing capacity as the ice deteriorates.

6.5. Lessons Learned

It was understood that this study was to be an initial effort toward a more complete understanding of oil spill response to an Arctic blow-out scenario. One of the products of the study would be an informed basis for further in-depth work in the future. A candid evaluation of the lessons learned provides a good starting point for future planning. For example:

- The broad nature of the initial data sought provided limited opportunities for statistical inference and trend analysis. For instance, this study did not thoroughly focus on the interaction between water, oil, and ice as it relates to the variables of salinity, temperature differences, viscosity, interfacial tension, ice structure and brine draining. Data from a comprehensive study of these variables and interactions could be of great use in the practical field application of oil spill response, collection and transport, and mitigation.
- Future planning should include experimental design focused on key areas thereby allowing for richer and more consistent data production.

- Due to the use of enclosed ice forms, there was a vertical salinity gradient in the ice as the rejected salt increased the salinity of the remaining liquid. As this high salinity and corresponding lower freeing point liquid freeze, the brine channels tend to increase in size within the ice blocks as a function of depth. In natural environments, the salinity of the water is stable and the size of the brine channel is relatively uniform and correlates to the ice temperature. A better approach would be to conduct the test on a free-floating ice sheet where the salt rejection would have minimal effect on the remaining solution. If a large cold room is not available, the ice forms could be filled with a water of a lower salinity (for example 14ppt) as the salinity in sea ice is on the order of 5ppt.
- Open manual spraying of crude oil on ice was messy and potentially unsafe for personnel conducting the application. This practice should be replaced by a safer, more controlled, and reproducible system. A possible solution could be to design a movable hood arrangement of fixed area with an internal manifold of precision spray nozzles arrayed for consistent oil deposition. This hood could be lowered to the ice surface to form a temporary seal thereby assuring more quantifiable oil deposition while limiting overspray and exposure to personnel of hazardous atmospheres.
- In the refrigerated trailers (CONEX boxes) the necessary linear arrangement of the ice forms, the need to keep the doors open while applying oil, and the refrigeration unit being at the front of the trailer all resulted in a temperature gradient in the boxes. This gradient is reflected in the internal temperature of the ice. The ice block layout will need to be considered as a variable in the data analysis, a fact that could have been avoided with a larger cold room.
- UV light sources were used to simulate the effect of sunlight on the ice/oil surfaces. This light source did not cover the full spectral range of true sunlight and did not produce an appropriate level of heat to which the surface would be exposed. Future planning should include actual sunlamps that produce sunlight exposure with greater fidelity. Further, a full range field spectrometer should replace the pyranometer for measuring this incident light and albedo during the investigation.
- Large labels should be placed on all target ice blocks and experimental vessels. These labels prove very helpful in clarifying photo/video documentation at later viewing and analysis.
- Close communication between field operations and the laboratory are essential. An improved system of communication would be of benefit in future testing.
- In the experimental design, trays with oil slicks were intended to provide baseline exposure of oil to the same environmental conditions to which the subject slicks on ice were exposed while eliminating the contribution of ice. Unfortunately, in the process of moving ice blocks and trays around to accommodate removal of rented refrigerated trailers, these baseline trays were inadvertently left out-of-doors at elevated temperatures for an undetermined amount of time. This invalidated any data obtained from these baseline trays. It is highly suggested that future studies utilize an experimental setup that may remain in-place and undisturbed throughout the experiment in order to reduce the possibility for error.

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Appendix A

Surface Temperature Before and After Oil Application					
Date	Deviations				
Test Day	Average	Median	Minimum	Maximum	Standard
Ambient Temp in 40-ft Reefer (°F)	4.87	-0.40	-4.00	45.50	12.95
Oil Temp	60.05	60.10	53.00	64.80	3.06
Temperature of Oil on Ice Block Before Application					
0.5 AC Start (°F)	10.46	8.00	-1.10	38.70	10.05
0.5 BC Start (°F)	9.29	6.40	-1.40	38.80	10.12
1A Start (°F)	-0.55	-3.15	-5.80	25.10	6.72
2A Start (°F)	0.40	-1.75	-5.10	28.20	7.04
3A Start (°F)	1.17	-0.65	-4.60	29.90	7.23
4A Start (°F)	2.43	0.70	-5.50	29.60	7.40
1B Start (°F)	-0.24	-2.15	-7.90	26.70	7.11
2B Start (°F)	-0.99	-2.90	-6.90	20.90	5.80
3B Start (°F)	0.66	-2.25	-6.50	44.20	10.15
4B Start (°F)	1.89	-0.80	-5.40	48.70	10.92
Temperature of Oil on Ice Block After Application					
0.5 AC End (°F)	27.15	25.80	17.40	42.90	6.52
0.5 BC End (°F)	26.60	24.85	16.00	42.40	7.20
1A End (°F)	1.25	0.40	-26.00	15.80	7.68
2A End (°F)	4.37	3.25	-0.50	19.30	4.10
3A End (°F)	8.04	5.95	1.80	47.30	9.23
4A End (°F)	12.14	11.15	0.90	30.40	6.57
1B End (°F)	2.73	1.95	-2.10	15.60	3.76
2B End (°F)	6.34	5.65	0.60	21.60	5.02
3B End (°F)	10.64	10.00	0.10	28.40	6.24
4B End (°F)	13.52	13.05	0.10	30.90	6.98
Change in Temperature of Oil on Ice Block					
0.5 AC Delta (°F)	16.39	17.60	-3.00	23.20	6.48
0.5 BC Delta (°F)	16.57	18.20	-2.00	22.40	6.05
1A Delta (°F)	1.80	3.20	-20.20	11.60	6.42
2A Delta (°F)	3.97	4.75	-8.90	10.20	4.00
3A Delta (°F)	6.87	6.75	-3.90	17.40	4.74
4A Delta (°F)	9.71	11.35	-2.00	15.20	4.86
1B Delta (°F)	2.97	3.75	-11.10	8.00	4.09
2B Delta (°F)	7.33	8.20	-4.10	16.10	4.54
3B Delta (°F)	9.97	12.10	-15.80	18.70	7.86
4B Delta (°F)	11.64	13.75	-17.80	20.00	8.65

Appendix B

Oil Application Lapse Time, Oil Weight and Rate					
Test Sample	Deviations				
	Average	Median	Minimum	Maximum	Standard
0.5 AC	0.00359	0.00359	0.00359	0.00359	
0.5BC	0.00369	0.00369	0.00369	0.00369	
1A	0.01175	0.01175	0.01111	0.01240	
2A	0.02259	0.02259	0.02236	0.02282	
3A	0.03387	0.03387	0.03374	0.03399	
4A	0.04464	0.04465	0.04444	0.04487	
1B	0.01153	0.01153	0.01147	0.01159	
2B	0.02265	0.02265	0.02265	0.02265	
3B	0.03358	0.03358	0.03340	0.03375	
4B	0.04468	0.04465	0.04444	0.04500	
Lapse Time (sec)	146.889	128.583	128.167	336.050	59.326
Oil Applied (lb)	22.458	21.955	16.030	26.420	2.524
Rate (lb/sec)	0.167	0.171	0.048	0.206	0.039