Remote Sensing of Oil In and Under Ice in a Climate-Controlled Test Basin

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Abstract (2017-111)

The ability to rapidly detect and delineate an oil spill in an Arctic environment is critical for efficient and effective response. The International Association of Oil and Gas Producers (IOSP), Arctic Oil Spill Response Technology – Joint Industry Programme (JIP) funded a novel controlled laboratory experiment to assess the relative efficacy of a variety of remote sensing instruments. This unbiased evaluation of existing and emerging technologies was recently conducted in the Ice Engineering Test Basin at the U.S. Army Engineer Research and Development Center's Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire, USA.

CRREL provided the unique testing environment for sensor evaluation using the 120 ft. long by 30 ft. wide by 8 ft. deep Test Basin. The refrigerated Test Basin was filled with a manufactured saltwater solution and an 80 cm sea ice sheet was grown with fifteen individual containment hoops. Within the individual containment hoops, oil volumes were injected at predetermined ice thicknesses leading to oil encapsulation at differing ice depths.

The Prince William Sound Oil Spill Recovery Institute assembled a team of remote sensing experts to select, operate and interpret sensors to examine and validate oil detection capabilities in level sea ice. Testing covered the full ice cycle from fresh oil and encapsulated oil in growing ice to migrating oil during ice melt out. Five aerial sensors were attached to a

cantilevered boom on a motorized carriage operating above the ice surface, while at the bottom of the tank were nine subsea sensors installed on a computer-controlled traveling underwater platform

Ice cores were obtained outside the hoops during ice growth and in designated hoops during the melt-out phase, with the objective of characterizing ice structure and oil migration using crystallography and CT scanning.

Environmental measurements that would affect sensor performance such as resistivity, acoustics, air, ice and water temperatures were also recorded.

This experiment provided a comprehensive side-by comparison of the sensors evaluated, while correlating measurements with the ice properties.

The paper will provide a full description of the hoop layout plan, the oil injection process, and the measurements schedule that minimized sensor interference.

INTRODUCTION

The Arctic Oil Spill Response Technology – Joint Industry Programme (JIP) – was initiated in 2012, to undertake specifically targeted research projects identified to improve industry capabilities and coordination in the area of Arctic oil spill response.

The JIP, managed by the International Association of Oil and Gas Producers (IOGP) is a collaboration of nine oil and gas companies (BP, Chevron, ConocoPhillips, Eni, ExxonMobil, North Caspian Operating Company, Shell, Statoil, and Total) which focused on six key areas of oil spill response: Dispersants; Environmental Effects; Trajectory Modeling; Remote Sensing; Mechanical Recovery and In-Situ Burning. One aspect of the JIP was Oil Spill Detection and

Mapping in Low Visibility and Ice which was done in two phases. The first phase was to identify viable remote sensing technologies (Puestow et al., 2013, Wilkinson et al., 2013). The effort in the second phase reported here was to evaluate the technology in a simulated Arctic environment. The evaluation was a partnership between the Oil Spill Recovery Institute (OSRI) located in Cordova Alaska and CRREL located in Hanover New Hampshire. The objective of this testing phase was to determine the conditions under which varieties of remote sensing systems located above and below the ice cover are able to detect oil on the surface, encapsulated within, or under sea ice. CRREL provided the testing environment to evaluate the sensors performance during the evolution of an under ice oil spill. Alaska North Slope (ANS) crude oil was injected under the ice surface at different stages of ice growth thickness. A variety of sensors were evaluated while detecting the injected oil layer from the time of injection, through continued growth of ice which encapsulated the oil, and into the melt out as the oil migrated through the ice. This was a unique evaluation as the respective technologies were compared side by side, detecting the same oil and ice conditions through the various ice phases. Data from the evaluation was used to develop and calibrate numerical models for extrapolating the sensor performance in the field.

The measurement team organized by OSRI includes researchers from EIC Laboratories, Boise State University (BSU), Inland Gulf Maritime (IGM), Cold Regions Research and Engineering Laboratory (CRREL), Woods Hole Oceanographic Institute (WHOI), Polar Ocean Scientific (POS), and Norbit. The modeling team includes researchers from the University of Alaska – Fairbanks (UAF), University of Washington (UW), BSU, and WHOI. (Pegau, 2017)

EXPERIMENTAL DESIGN METHOD

1. Facility details

Evaluation of the sensors was conducted in the Test Basin of the Ice Engineering Facility at Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, NH. The basin is 37 m long (X axis), 9 m wide (Y axis) and 2.4 m deep and is housed within a refrigerated cold room. The room can be refrigerated as low as -28°C using low velocity refrigeration units mounted on the ceiling 4.3 m above the water surface. Low velocity fans provide a quiescent environment for freezing level ice with uniform thickness.

Salt (NaCl) was mixed with fresh water to achieve a starting salinity of approximately 28 parts per thousand (PPT). During the freezing process as the salt was rejected during ice growth, the salinity of the remaining water increased to 38 PPT by the end of the test Salinity profiles were measured in the ice core and water throughout the experiment. Ice cores were later analyzed using high resolution CT-imaging. The characterization of ice structure and quantification of brine channel voids lessened ambiguity from a number of sensors evaluated in this experiment.

Three test carriages are utilized in test basin; main carriage, personnel carriage and an underwater carriage.

The blue main blue carriage (Figure 1) travels on rails over the length of the basin using a rack and pinon drive system. The speed of the carriage is adjustable from 1 cm/sec to 2 m/sec using a two speed gear box and variable frequency drive (VFD) fixed to the drive motor. The heated control room on the carriage was used for instrumentation communications and data collection. While the main carriage was not in use, it was parked in the preparation area on the east end of the basin. This area can be isolated from the main area by a vertical lift door (red frame in Figure 1) and the temperature is controlled independently from the main basin. Aerial sensors were mounted 2 meters above the ice using a boom cantilevered off the main carriage. Sensors were mounted 5 meters in front of the carriage to avoid having the main carriage in the field of view of the sensors. The boom travels east and west through the centerline of the test basin.

Figure 1: Main Carriage with aerial sensor boom

The yellow personnel carriage also spans the basin and is mounted on rubber tires that travel on the walkways outside the basin as seen in Figure 2. The pneumatic tires allow bounce in the carriage under live load and is used primarily to provide access when the ice is unsafe. The personnel carriage is available for equipment that does not require a stable platform. Beams on the front of the personnel carriage were used to mount a light source that acted as an artificial sun for sensors located above and below the ice surface.

Figure 2: Personnel carriage (left) and Main carriage (right)

The sub-surface sensors were mounted on an instrumentation platform that sits on a motorized underwater carriage. The underwater carriage rides on parallel rails attached to the floor of the test basin as seen in Figure 3. The carriage is propelled down the tank using a stationary chain and cog drive with the cog driven by a servo motor mounted to the carriage. The position of the underwater carriage is repeatable within a half centimeter along the length of the basin using computer control. Underwater sensors were mounted to a retrievable instrumentation platform that was pin registered to the underwater carriage. This allowed the suite of instruments to be removed from the water for servicing if necessary.

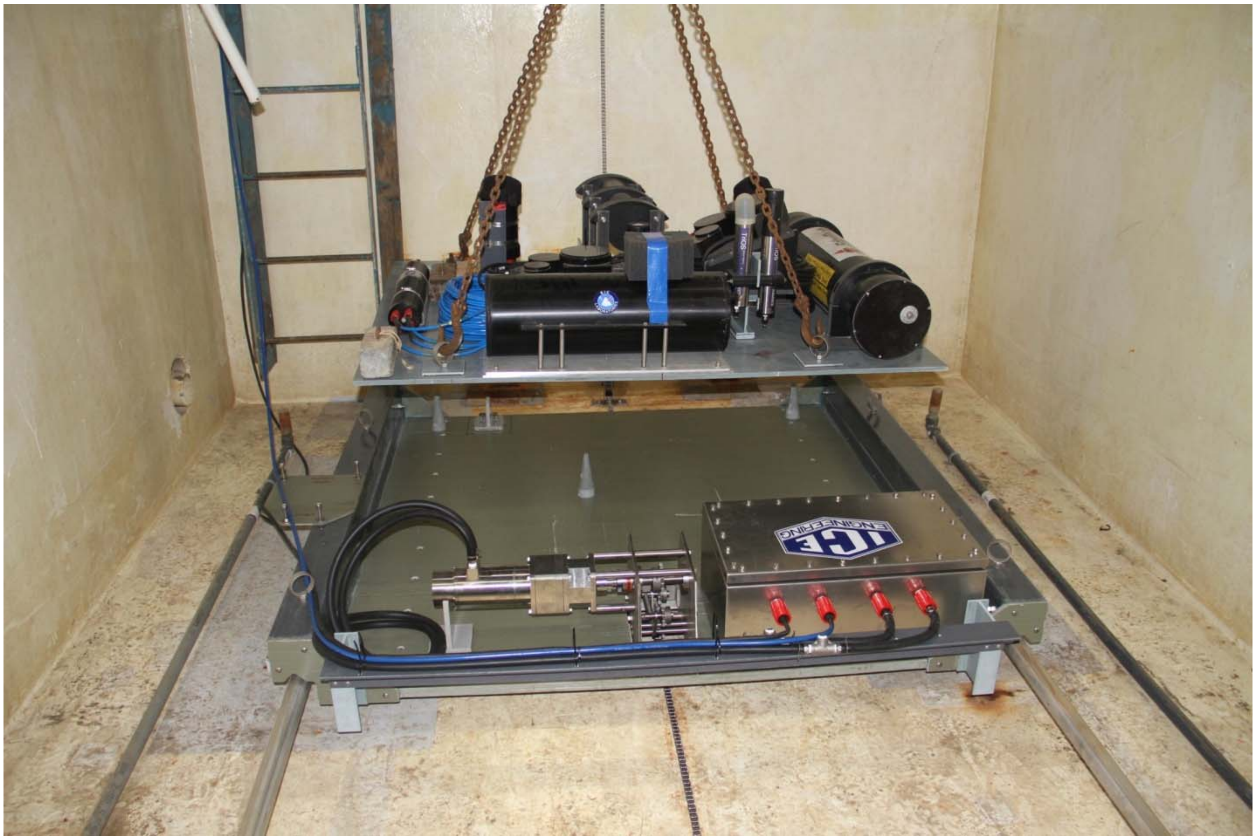

Figure 3: Motorized carriage (bottom) and instrumentation platform (top)

2. Test Layout

The test basin was subdivided into test areas using rectangular containment hoops as shown in Figure 4. Hoops were fabricated using 4 inch diameter PVC pipes as frames with 13 oz vinyl coated polyester tarps with sleeves for the PVC frame. The sleeve and vertical overlap were glued together to maintain a continuous oil barrier. The curtains hung below the ice surface where they could contain the injected oil during the oil injection process. Hoop curtain lengths were designed to hang 15cm deeper than the target ice thickness at the time the oil would be released into the respective hoop. The depth of the curtain under the ice was kept as short as possible in order to avoid having the curtain block the view of the oil by low angle of incidence sensors.

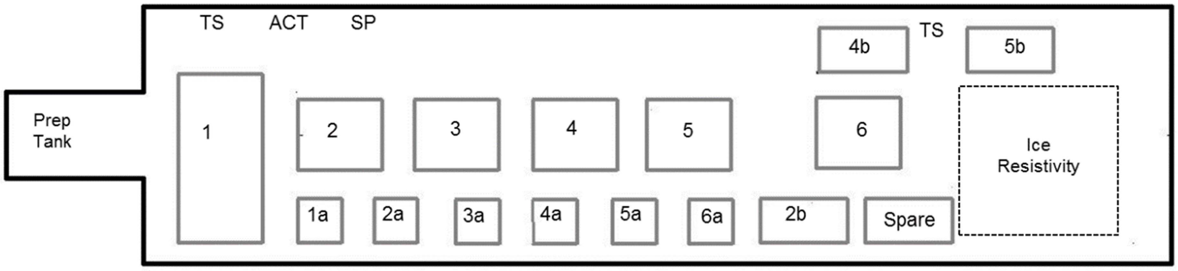

Figure 4: Test Layout

Primary hoops (1-6) were on the centerline of the tank and in view of all the submerged and aerial instruments. The area between hoops along the centerline was reserved as a control for both submerged and aerial sensors during the full ice scans. Hoop 1 was 3m long (X axis) by 6 m wide (Y axis) and remaining primary hoop (2-6) were 3m long and 2.5 m wide. Hoop 1 was larger and shifted towards the north wall of the basin to evaluate the side looking capability of the multi-beam sensor. Hoop 1 was the only hoop that supported multiple spills. For invasive physical testing and to characterize the oil migration through the ice during the melt out phase, secondary hoops designated with an "a" suffix were off centerline and not monitored by the instrumentation. All activities that were conducted in the primary centerline hoops were duplicated in the secondary hoops. Secondary hoops were 1.5m by 1.5 m and subjected to the same oil injection thickness and temperature conditions as their associated primary hoop.

Special purpose hoops designated with a “b” suffix were off center and monitored by a sub-set of the sensors to be compared to the corresponding primary hoop.

Sensors installed in the ice include two temperature strings (TS), sound propagation (SP) and an acoustic calibration target (ACT) as noted in Figure 4. The two temperature strings were installed approximately 10m from each end of the basin near the south side. Temperature strings were fabricated using Resistance Temperature Detectors (RTD’s) starting 10cm above the surface to 100 cm below the surface. RTD’s were spaced at 5cm increments until the temperature string reached a depth of 1.4 meters. At that point the spacing between RTD’s was increased to 15cm. Output of the temperature strings were recorded with a CR1000 Campbell Scientific data logger. Ice temperature from the west temperature string is plotted in Figure 5.

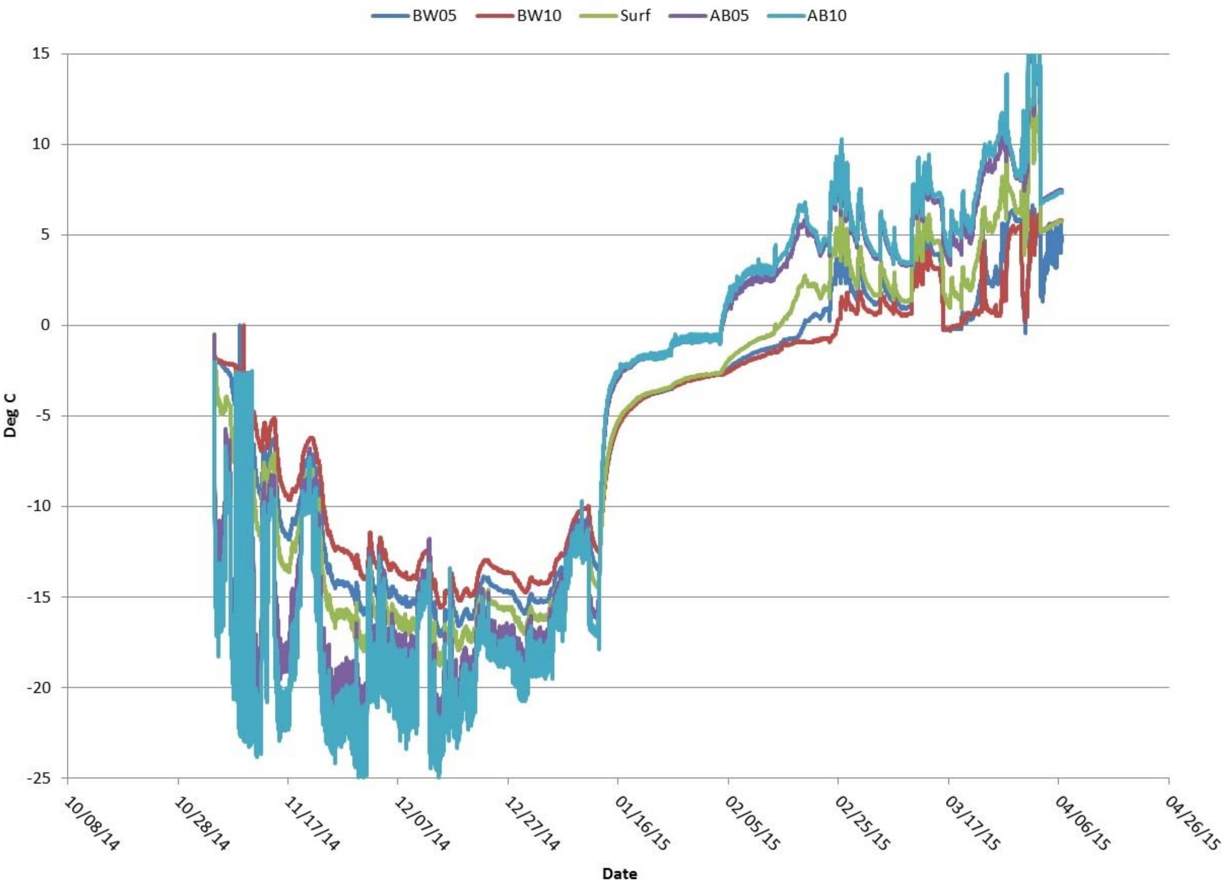

Figure 5: West side temperature string response.

The SP system and the ACT shown in Figure 6 were installed prior to freeze up and monitored by Woods Hole Oceanographic Institution (WHOI). These systems were instrumental towards the calibration of sonar equipment evaluated during the experiment.

Figure 6: SP (left) and ACT (right) environment calibration sensors shown in empty test basin.

A 50cm x 50cm three dimensional resistivity array (Figure 7) was installed by the Boise State University team in the northwest corner of the test basin. This position minimized interference with other radar measurements. The 72 electrode array was used to measure ice resistivity using a standard commercial processing software.

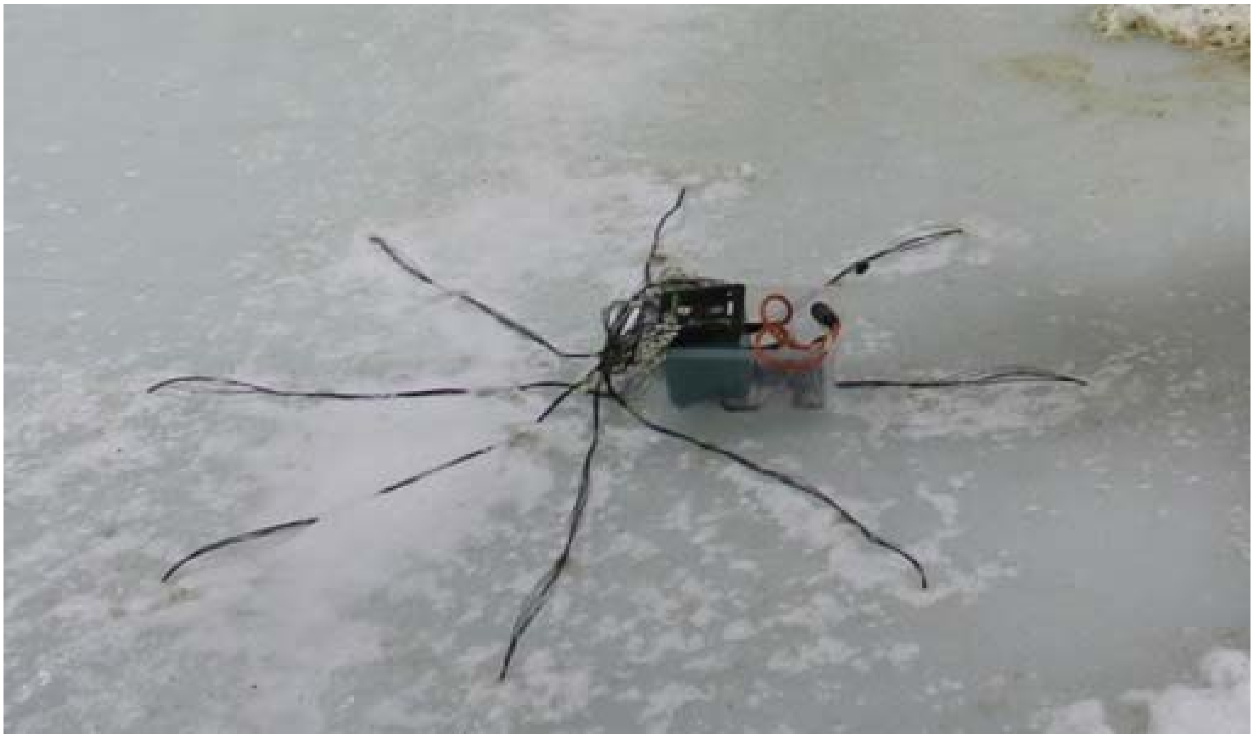

Figure 7: Boise State University Resistivity Array

3. Oil Injection Matrix

The experimental parameters for the hoops are listed in Table 1 and 2. Each set of hoops were designed to assess a single variable (ice thickness or oil thickness) to determine change in system performance. The anticipated growth of ice after the oil injection provided the underwater sensors the opportunity to monitor the encapsulation process as ice formed under the layer of oil.

Configuration of Primary and Secondary Hoops						
Hoop ID	Dimension (L x W)	Curtain Depth	Surface Ice @ Freeze up	Ice Thickness @ Oil	Nominal Oil Thick	Remarks
	m	cm		cm	cm	
1	3 x 6	100	grease	5cm Frazil+	0.5	test multi-beam system. Start with grease ice spray oil in surface and mix. See Recycle of Hoop 1
2	3x2.5	35	columnar	20	2	thin ice with oil encapsulation
3	3x2.5	50	columnar	35	1	mid-thickness ice with thin layer of oil that will be encapsulated. Compare with 3,4,and 4b
4	3x2.5	50	columnar	35	5	mid-thickness ice with thick layer of oil that will be encapsulation. Compare with 3,4,and 4b
5	3x2.5	70	columnar	55	2	Thicker ice with encapsulation . Compare with 2 and 5b
6	3x2.5	100	grease	80	4	Thick ice thick oil prior to melt out
Reinject 1	3 x 6	100	second spill	35	2	test multi-beam system with under ice spill
Designated "a" control hoops corresponds with primary hoop, duplicating oil and ice conditions. Ice will be used for destructive testing during melt out phase.						
1a	1.5x1.5	100	grease	5cm Frazil+	0.5	See Recycle of Hoop 1
2a	1.5x1.5	35	columnar	20	2	thin ice with oil encapsulation
3a	1.5x1.5	50	columnar	35	1	mid-thickness ice with thin layer of oil that will be encapsulated. Compare with 3
4a	1.5x1.5	50	columnar	35	5	mid-thickness ice with thick layer of oil that will be encapsulation. Compare with 4,and 4b
5a	1.5x1.5	70	columnar	55	2	Thicker ice with encapsulation . Compare with 5b
6a	1.5x1.5	100	columnar	80	4	Thick ice thick oil prior to melt out

Table 1: Configuration of Primary and Secondary Hoops

Supplemental Hoops- Compare with the Corresponding Primary Hoop						
2b	3x 1.5	100	columnar	20-35	2	Warm oil to test infrared oil detection
4b	3x 1.5	50	columnar	35	.5 to 5	Mid-thickness ice with thick layer of oil that will be encapsulated. Compare with 3,4,and 4b Fixed underwater sensors with continuous monitor
5b	3x 1.5	70	columnar	55	2	Thicker ice with encapsulation Compare with 5 Fixed radar 2M above the ice with continues monitoring
6b	3x 1.5	100	columnar	80	4	Oil on the surface

Table 2: Configuration of Supplemental Hoops

The initial condition for Hoop 1 was 5cm of slush ice that was created by breaking up the ice within the hoop and adding frazil ice generated in an agitated sea water tank. Once the desired ice condition was created, an equivalent 0.5 cm oil slick (900 liters) of oil injected was in and under the slush. A similar process was conducted in Hoop 1a to replicate ice conditions.

As the ice reached the target thickness on the remaining hoops Alaska North Slope (ANS) crude oil was injected under the ice in within the hoop. ANS crude oil was stabilized at a temperature of approximately 0°C. A lobe pump designed for low viscosity oil was used to inject the oil. Pumping speed was controlled by a variable frequency drive. Oil was delivered within the containment area using a custom delivery tube. The delivery tube was inserted through an access hole adjacent to the containment area. To avoid injecting air under the ice, the control valves on the oil pump system were configured to draw water out of the basin with the pump discharging into a waste tank on the main carriage. With the air purged, the delivery tube was rotated towards the center of the containment hoop. Valves on the pump system were then reconfigured to draw from the ANS oil tote on the main carriage and discharged via the custom tube under the ice as seen in Figure 8. Once the volume of oil that corresponds to the nominal oil thickness defined in Table 1 was injected under the ice, the oil delivery line was purged using the water in the waste tank. Oil injection was monitored using a high definition underwater video camera mounted on the underwater carriage and a second video camera in a cored hole outside the containment area for a second perspective.

Figure 8: Subsurface image of ANS oil as it is injected into a containment hoop.

Hoop 2 was injected when the ice was 20cm thick, but during the oil injection, some of the oil migrated to the containment curtain where the ice was slightly thinner. To avoid oil collecting along the curtain, the remaining hoops were covered with insulation approximately seven days prior to injection. The insulation was installed with a 15cm border of exposed ice along the hoop to create a depression on the underside of the ice, resulting in more uniform sub-surface ice.

Hoop 3 and 4 were injected with the same target ice thickness of 35cm, but with different equivalent oil slick thicknesses of 1cm and 5cm, respectively. Figure 9 shows Hoop 3 back lit with the underwater lights to show the oil slick following the injection.

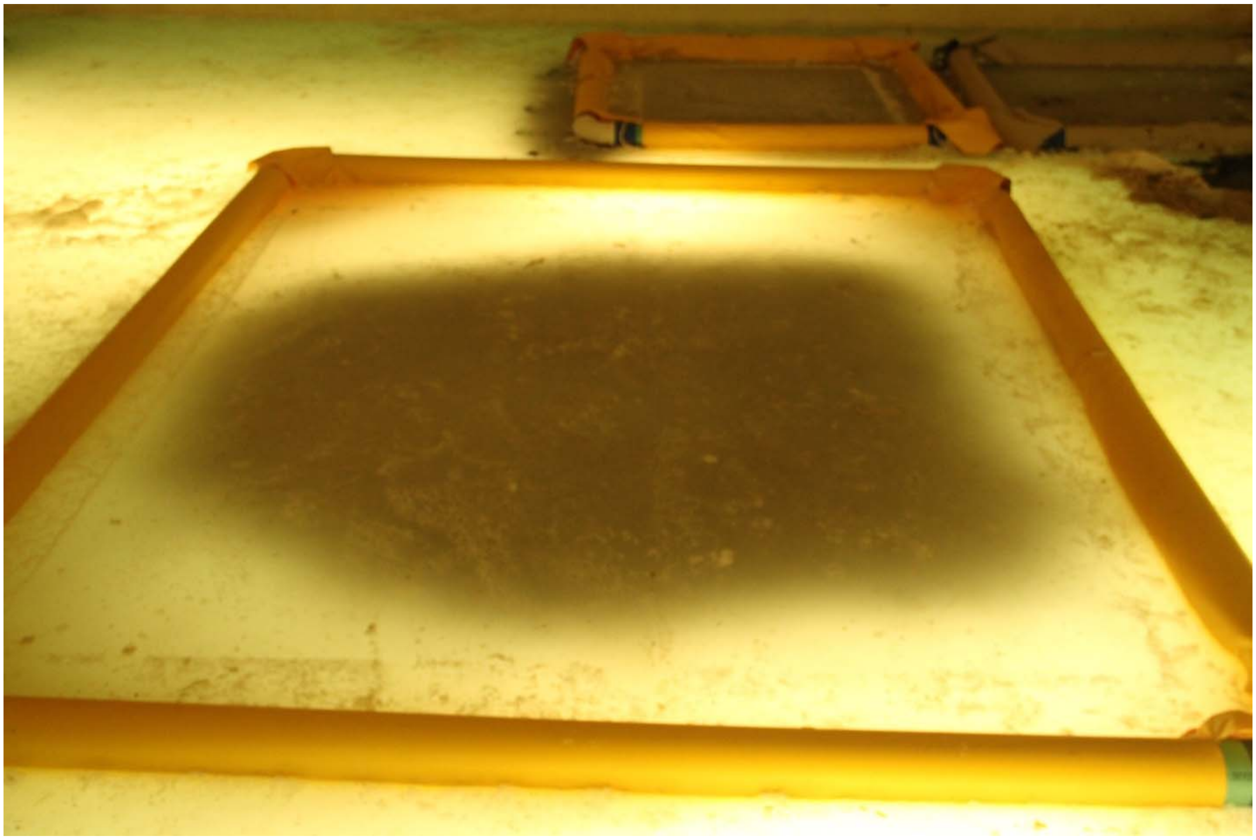

Figure 9: Hoop 3 with back lighting following oil injection.

Hoop 5 was injected when the ice was 55cm thick with an equivalent slick thickness of 2 cm of oil.

Hoop 1 was reinjected with an equivalent oil slick thickness of 2 cm when the ice was 30cm thick. The multi-beam sensors monitored the injection real-time. All oil spills were timed to allow encapsulation of the oil with the exception of Hoop 6, which that was injected with oil when the ice was 80 cm thick, just prior to the melt out phase.

4. Sensor Data Collection

The primary hoops were discretely monitored by moving the respective carriage (aerial and submerged) into position and taking measurements with the sensor suite in a designed order. The order of data collection was designed to prevent sensor to sensor interference. The standard procedure for each hoop was to collect measurements from all sensors just prior to oil injection, immediately after injection and two hours after injection. The hoop sensor data was collected twice a day for the next three days, then on a weekly basis through the duration of the experiment.

Data was also collected continuously as the carriage traveled from one end of the test basin to the other. This "sweep" of data was requested by researchers to develop a continuous survey of the entire ice sheet and was collected weekly at a minimum.

The supplemental "b" hoops were used to evaluate a single variable subset of the sensors. Hoop 2b was used to evaluate if "warm" oil injected under the ice could be detected with infrared imagery. Hoop 4b was used to continuously monitor the encapsulation of the oil using a subset of the underwater sensors. Hoop 5b was used to continuously monitor the oil spill with a Frequency Modulated Continuous Wave (FMCW) sensor. Oil was also spilled on snow for detection by the FMCW system

5. Characterization of the ice

The evaluation was designed as a simulation of first-year Arctic sea ice, which is flat and uniform in thickness with columnar crystal structure. As a review, as the water freezes, crystal dendrites extend down into the water column, rejecting the impurities in the freezing process.

This delicate matrix of ice crystals is referred to as the skeletal layer and is relatively porous with an ambiguous ice-water interface. As the skeletal layer solidifies, the salt between the crystals are trapped, creating brine channels between the vertical ice crystals.

When oil is released under the ice it replaces water within the skeletal layer. If the added volume is small, the dendrites still extend beyond the oil layer, resulting in an irregular subsurface interface. Without the irregular underside of the ice, the interface is problematic for some instrumentation, causing weak reflected signals for sonar and acoustic systems. An oil saturated skeletal layer results in a stronger signal response for particular sensors..

To characterize the ice freezing phase of the experiment, ice cores were obtained adjacent to the hoop being injected (Figure 10) at least once a week using a 7 cm CRREL core barrel. A minimum of three cores recovered the following: (1) temperature and salinity profiling at 5 cm increments and density measurements every 10 cm, (2) analysis of the cystography (3) Micro CT scans. The Micro CT scans were at a resolution of 30 microns providing 3D descriptions of the air, brine and oil inclusions and voids in the ice (Courville, 2017).

Figure 10: 7cm diameter ice core

CONCLUSIONS & LESSONS LEARNED

The research teams were on-site for sensor placement on the aerial and submerged platforms, and for the first two experimental oil injections for initial data capture and potential equipment troubleshooting. All equipment was operated by CRREL staff when the primary sensor operators were off-site during the later parts of the experiment. Explicit instructions regarding, start up, stand by, data collection, troubleshooting and shut down protocols were provided to the CRREL team prior to experimental set-up by the primary operators. When a piece of equipment failed during any portion of the experiment, basic troubleshooting techniques were used by the CRREL staff before the corresponding research team was contacted. In some cases a piece of equipment was left inoperable after repeated sensor failures. All attempts were made to repair faulty equipment while not jeopardizing the overall experimental design objectives. The ability to recover the underwater sensor platform for sensor adjustments and repairs was essential to success.

Irregularities in the sub surface water and ice interface was a concern when oil was injected into Hoop 2. The PVC and vinyl hoop was more of a heat load than anticipated, causing faster ice growth in the center of the hoop than around the edges. This was countered by adding insulation to the center of all Hoops when sensors were not actively recording data. This allowed a more uniform ice growth. The presence of the hoop likely has an effect on the crystal structure of the ice. It is advised to design the hoop sizes as large as reasonable to avoid that effect.

Hoop curtains were designed to keep the oil in a specific area and were kept as short as possible to allow off-angle sensor measurements. In one case hoop edges froze into the ice and cause a small oil seepage into the test basin. The solution is to weigh down the coop curtains to prevent floating and freezing into the ice sheet.

An interesting observation was that heat generated from the underwater instrumentation caused small air bubbles to float up to and imprint onto the sub-surface of the ice. Proper insulation of instrumentation possibly would have prevented that minor inconvenience.

The final ice thickness of 80 cm was a difficult task. The injected oil layers impede ice growth. Continuous personnel activity in the test basin causes higher than normal humidity levels that led to frequent defrost cycles, resulting in shorter refrigeration cycles. A thicker ice sheet could have been achieved in a shorter time with less personnel interference.

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