PHASE I SUMMARY REPORT FOR DEPLOYABLE SYSTEM TO RECOVER OIL UNDER SOLID ICE (ORUI)

Summary Report

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TABLE OF REVISIONS

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-	05/20/2021	Advance Release	QC	JS	RL
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Executive Summary

In response to Bureau of Safety and Environmental Enforcement (BSEE) solicitation 140E0120R0001 for Development of a System for Oil Recovery Under Solid Ice (ORUI), Phoenix International Holdings, Inc. (Phoenix) was pleased to propose a Remote Environmental Module for Oil Recovery in the Arctic (REMORA). This novel oil recovery technique will be capable of dislodging crystallized oil from the undersurface of ice sheets under arctic conditions.

The objective of this project is to design and test an underwater deployable tooling system capable of detecting, inspecting, and recovering pockets of oil floating in crevasses under the ice in the Arctic. The goal, to meet the BSEE Under Ice Oil Recovery System requirements by the design of an Oil Recovery System (ORS) tool skid designed for "plug and play" standardized (power and data) integration utilizing the expansion ports of the qualified ROV for ease of integration and operation.

More specifically the Scope of Work (SOW) outlined in Phoenix's contract and related Work Breakdown Structure (WBS) included:

- Preliminary tool skid design
    - Study and implementation of a visualization method to discern oil, scraping method to dislodge solidified oil crystals, integration of a pumping system and a locator system capable of mapping as well as returning to a previously recorded location.
- Detailed tool skid design
    - Prepare final design specifications, documents, and drawings for the ORUI system.
- ROV host study and technical requirements document
    - Carry out an ROV Host Trade Study to verify the feasibility for the implementation of a more compact ORUI system.
- ROV selection and quotation
    - Complete the ROV Host Study culminating with a selected commercially available ROV(s) capable of handling the system operational requirements. This selected ROV is quoted for purchase and cost details are included in the cost estimate report REF 7.
- Deliverables
    - Develop a completed system design package that shall include dimensional drawings, schematics, component list and any other documents necessary for BSEE to be able to review the system design.

This report minimized developmental risk by idealizing proven off the shelf components with minimum integration development; this approach enabled detailed but simple management of the effort, risk, and funds.

PHASE I SUMMARY REPORT

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1.0 INTRODUCTION

Phoenix International Holdings, Inc. (Phoenix) has completed the Phase I tasking "Development of a System to Recover Oil Under Solid Ice" under contract 140E0120C0006. This summary report summarizes the trade-off studies and analyses conducted, summaries of discussions and meetings with ROV manufacturers, recommendation for selected ROV, and other selected components such as the pump, lighting, navigation systems for the Oil Recovery Under Ice (ORUI) system. A recommended ROV (SAAB Cougar XTi) is presented as well as the design of the primary subsystems of the ORUI.

2.0 REFERENCES

[1] DOC10036092A ORUI ROV HOST TRADE STUDY REPORT
[2] DOC10036187 TOOL SKID DESIGN REPORT
[3] DOC10036189 SCRAPER HEAD TEST REPORT
[4] DOC10036188 SUCTION NOZZLE TEST REPORT
[5] DOC10036191 UV LIGHT OIL DETECTION TEST REPORT
[6] ABS RULES FOR BUILDING AND CLASSING UNDERWATER VEHICLES, SYSTEMS AND HYPERBARIC FACILITIES – 2017
[7] DOC10036193 COST ESTIMATE REPORT

3.0 BACKGROUND

In February 2018, CRREL successfully demonstrated a method to move pockets of oil trapped under ice using a Seabotix ROV equipped with an air delivery system. This test was conducted at CRREL's outdoor saltwater tank in which was grown a solid ice sheet of approximately 8-10 inches thick. Several pockets were developed on the underside of the ice, and crude oil was injected under the ice into these pockets. The ROV was sent under the ice to view the oil and to move the oil out from the pockets to channels cut in the ice for topside recovery. The prototype was successful at moving the crude oil out of pockets formed in the underside of the ice. However, the dislodged oil was difficult to direct to the channels using the air delivery system. At the end of the demonstration, inspection of the ice revealed that within a short period of time oil began to crystalize into the underside of the ice sheet and move up through the brine channels formed within the ice. These newly formed crystals were able to be easily scraped off the ice.

The Phoenix ORUI project builds off the lessons learned from the previous demonstration to design a system to extract spilled oil trapped underneath a solid ice sheet in addition to dislodging any frozen oil crystals from the ice. The required specifications for the ORUI system are summarized below:

- Recover and remove volumes of oil in pockets located on the underside of ice at a minimum rate of 15 gallons per minute.
- Provide clear imaging from under the ice to the remote user
- Provide the ability to differentiate between ice, oil, and water.
- Scrape the underside of the ice to remove newly formed oil/ice crystals.

- Recover oils of various viscosities. The system will be tested with a crude oil expected to have a viscosity of around 10-5,000 cp at 32 degrees F.
- Operate in arctic ice conditions with temperatures below 32 degrees F and underwater at 32 degrees F.
- Travel under ice for 250 ft to recover oil and return to the retrieval location.
- Operate in water depths between 8-60 feet (Shallow depth of 8 ft reflects the depth of the test tank at test facility).
- ROV will have an operating depth rating of 984 ft (300 meter) or greater.
- Water salinities between 0 - 35 ppt.
- Temperatures of -20F to 120F.
- Water temperatures from freezing up to 150F.
- Functions including light, vacuum, and recording of location data shall be easily activated and deactivated by the user remotely from a control unit.

These requirements will serve as the basis for the down selection of ROVs by size as well as support equipment selection.

4.0 ORUI SYSTEM DESIGN

4.1 Methodology

The ORUI system comprises four main subsystems: 1) the host ROV selection, 2) oil pumping system, 3) oil detection, imaging, and navigation system and 4) oil recovery and scraping system.

The host ROV and oil pumping systems are intimately related based on size and capacity requirements for the pumping system. As such the initial tasking was the identification of a suitable pump and motor combination to support the high-volume flow rate requirement of 15 gpm. The large pump and motor combination assembly has a significant impact on the size of the selected ROV. Once the pump and motor assembly were selected a list of 36 candidate ROVs was generated and then down selected to meet the specifications based on payload capacity, thrust to drag factors and the ROV power source, i.e., hydraulic, or electric. Three candidate ROVs were identified and then through subsequent quoting and design discussions with the ROV manufacturers a single ROV was selected as the recommended host ROV. Upon selection of the three candidate ROVs, the ORUI tool skid carrying the pump motor assembly was designed to attach to the undersurface of the ROV. Supporting subsystems for oil detection and imaging and ice capture/scraping were then developed to facilitate the oil recovery. A manipulator mounted scraper and nozzle assembly captures the oil which is transferred to the surface by the ROV mounted pump via a transfer hose. An imaging system consisting of cameras and lights and navigation system including an upward facing DVL and altimeter are used for ROV positioning underneath the ice sheet. This allows the ROV to fulfill the requirement of returning to a specified location if need be.

For a complete oil extraction cycle, the ROV would be deployed to extract oil from a targeted location. On arrival, the ROV will rely on the imaging system to be able to detect the presence of oil. Once oil is detected, the scraper and nozzle assembly will capture the oil and dislodge oil crystals for extraction by the pump. The pump discharge will be sent to a reservoir at the surface for filtration and separation. The complete ORUI system package is presented in Figure 1.

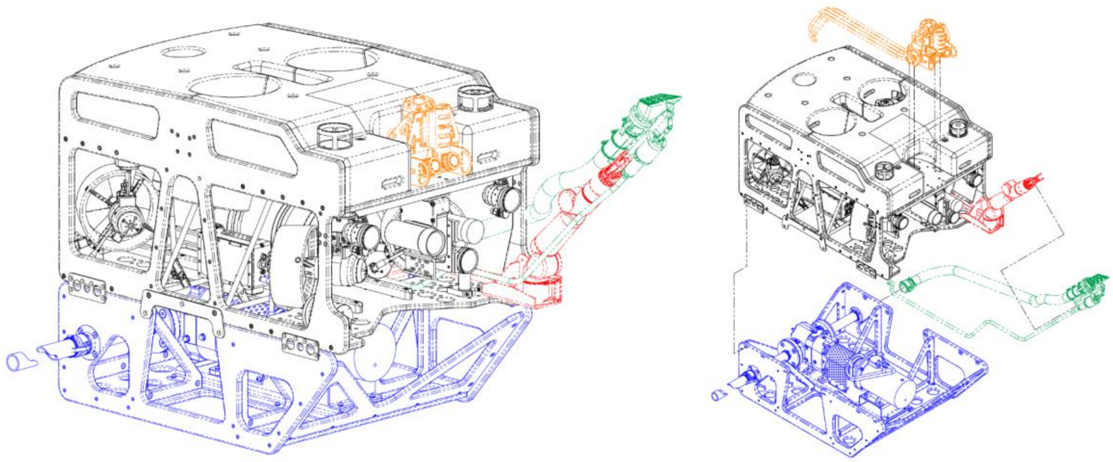

Figure 1: ORUI System

4.1.1 ROV Selection

The ORUI system is built around a ROV which serves as the foundation of the deployable system. The ROV down selection method and calculations are detailed in the ROV Host Trade study Report *[1]*. In carrying out this trade study, 36 commercial off-the-shelf ROVs were compared based on contract specifications and operational requirements to narrow the choice down to three ROVs.

In the first stage the ROVs were divided into groups based on sizes of small (less than 40 inches in any dimension), medium (between 40”-60” in dimension) and large (greater than 60” in dimension). Based on the minimum operational depth of 8’, the large sized ROVs were eliminated due to the tight space especially with a pump skid attached underneath.

Further ROV down selection was performed by identifying all supporting equipment necessary to achieve all contractual objectives for navigation, oil detection, scraping and extraction. The largest piece of equipment was the pump and motor. The Lobe Pro CS16p pump and 10hp Seatec submersible motor (TMUB112-2, AISI316L) were selected. This choice was based on the ORUI system requirement to pump 15 gallons per minute of oil with a viscosity range of 10-5000 cP at 32 degrees F. Details of the selection of this pump are presented in REF 1 along with other hydraulic pump options. The Lobe Pro pump and Seatec motor combination was ultimately selected based on performance specifications and ease of integration within an electrically powered ROV. A buoyancy foam calculation was also performed to determine the amount of foam necessary to reduce the pump mass impact upon the performance of the host ROV. Once the other subsystem equipment was defined the overall drag of the ORUI host ROV and equipment was calculated for comparison with the ROV thruster specifications to ensure the system was capable of carrying the associated equipment. The sum of all drag forces imparted on the ROV, pump skid and hose were all calculated and summed to provide the total drag on the system. A drag coefficient of 0.3 and water velocity of 1 knot were assumed for the purpose of these calculations. These drag calculations and results are presented in detail in REF 1.

The final ROV selected was the Seaeye Cougar XTi from SAAB. This ROV weighs 959 lbs. with a power draw of 20KVA. It possesses six thrusters (four horizontal, two vertical) delivering an overall forward thrust of 374 lbf. Figure 2 shows the Seaeye Cougar XTi dimensions. Quoted cost information of the SAAB Seaeye Cougar XTi is included in REF 7.

Figure 2: Leading ROV Option – Saab Seaeye Cougar XTi

4.1.2 Oil Extraction System

An important part of the extraction process is the tool skid (pump and motor) unit, which is also the largest system, by mass, other than the ROV, within the ORUI system. To meet the contract requirements (pump oils of various viscosities between 10-5000 cP at a flow rate of 15 gallons per minute) three pumps were identified for consideration. Keeping in mind the preference of having a light system, it was important to minimize the pump skid weight as much as possible. The Lobe Pro CS16p pump and 10hp Seatec submersible motor combination were selected for the ORUI system. Even though the Lobe Pro/Seatec combination was approximately 30% heavier than the hydraulic pump systems, this pump was selected based on the advantages of a significant reduction of power requirements, eliminating the need for an additional umbilical cable, lower umbilical cable size, and lower overall vehicle weight and size. More of the selection process is covered in the REF 1. Figure 3 presents the Lobe Pro/Seatec motor combination pump assembly. A structural analysis was performed on the tool skid to ensure the integrity of the skid to support the weight of the pump motor combination and the weight of the ROV. The skid material properties were derated and dynamic factors applied per the methods defined in ABS Rules for Building and Classing Underwater Vehicles, Systems and Hyperbaric Facilities - REF 6.

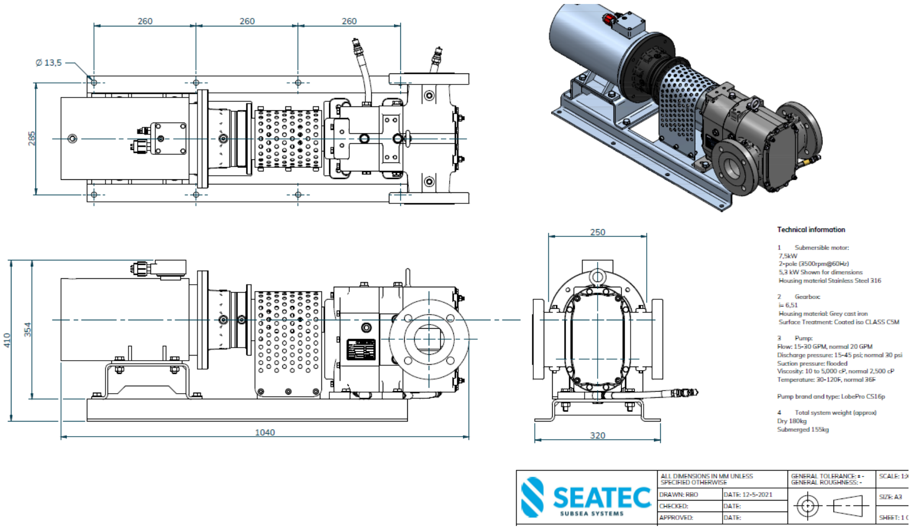

Figure 3: Lobe Pro CS16p pump and 10hp Seatec TMUB112-2, AISI316L motor

4.1.3 Oil detection, Imaging and Navigation Systems

The oil detection system will be composed of cameras and UV-LED lights pointing upwards, underneath the ice surface. ROV cameras and spare ports will be used to connect and control the UV light intensity, and one or two ROV cameras. Oils, which consist of hydrocarbon compounds, are excited by ultraviolet wavelengths and generate fluorescent reflections in the visible wavelength range from 400-600 nm. This characteristic will be used to help differentiate ice surface from oil pocket reflections. The ORUI ROV pilot will still rely on front cameras and regular LED lights for other visual references.

The up-looking camera video signals can either be digital HD or analog NTSC. Our initial experiments demonstrated that 380 – 395 nm excitation successfully provided visual identification of fluorescence of diesel and other concentrations of crude oils when using digital or analog cameras. The imaging of oil under ice remains susceptible to environmental lighting (sun angle), back scatter from waterborne particles in the water, and ice sheet thickness which drastically change the visual conditions under the ice.

For future expandability, the selected Seaeye Cougar XTi ROV from Saab has spare ports for COTS sonar and a laser light for easy integration. A combination of systems, such as adding a single-beam upward-looking sonar or laser lights may enhance the capabilities of the simple camera-uv light oil detection system. The addition of a sonar or a laser light can help identifying pockets of oil trapped within layers of ice. The sonar and laser light enhancements are not included in the current design but are mentioned here due to the expansion capability yielded by the Cougar XTi ROV.

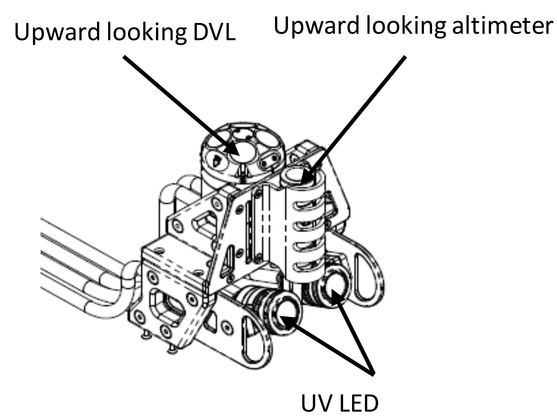

Figure 4: ORUI Navigation and Imaging System

Locating oil pockets relative to vehicle transects during the survey will be accomplished using an underwater GPS system. This technology uses a surface digital position computing board to calculate the position of a locator relative to the position of the receivers. The locator installed on the ROV transmits an acoustic signal which is picked by the receiver antennas installed at the ROV launching coordinates. The topside positioning computer triangulate and calculate the position of the locator based on the received signals from the antenna. Once the survey of the area is complete, the GPS log will be utilized to navigate back to the specific areas of interest for oil recovery and processing.

The navigation system (see Figure 4) consists of an upwards looking Doppler velocity logger (DVL) with a high-frequency acoustic narrow beam for close quarters range, coupled with a short-range altimeter for measurements of distance under the ice. Both the DVL and the altimeter are integrated to the ROV control system for navigation accuracy. These sensors are used to implement computer aided pilot functions such as auto altitude and station keeping. Although not specified in the project requirements, the advances in ROV technology guide the demand for more ROV control autonomy and less operator involvement, thus minimizing errors caused by lack of training, fatigue, or other human factors. This aspect was highly considered in the selection of the Cougar XTi ROV over the Cougar Compact ROV. Although the Compact ROV was lower in weight, size and had more propulsion to weight ratio, the XTi had a modernized control system. It is important to clarify that the Compact ROV control system could not be upgraded to perform station keeping or other enhanced control capabilities, according to SAAB, unless an expensive re-design and replacement of topside and subsea parts were performed. This would have left the ROV Compact operators with a mainly manually operated system.

4.1.4 Oil recovery nozzle and scraper system

The oil recovery nozzle and scraper system of the ORUI system is the primary interface between the operator and the oil to be recovered. This system is handled via a five-function manipulator controlled by the ROV pilot through a joystick interface to position the suction nozzle and or scraper to recover the oil. The primary method is recovery of pooled oil through the suction nozzle by directing the nozzle to the oil location and engaging the pump. The manipulator then allows the operator to sweep the nozzle through the pool similar to using a household vacuum to clean a floor. A secondary function is after pooled oil is recovered additional oil may have become crystallized or trapped in the lower approximately half inch thickness of ice as was observed during the original 2018 CRREL testing with the Seabotix ROV and an air jet system to corral a pool of oil for further recovery. Phoenix has developed a rotary scraping system to abrade the ice surface creating loosened ice particles carrying oil. Once sufficient oil carrying particles are generated by scraping these can be recovered by rotating the manipulator to position the suction nozzle to recover the oil particles. Several design iterations were developed and tested for both the nozzle construction and the scraper driving system. A rotary scraper driven by a submersible electric motor was the final design configuration and is shown in Figure 5. Other scraper blades and an oscillating driver system were considered and tested along with the rotary driven scraper as discussed further in REF 1 and REF 3. The scraper tool is firmly attached to a manipulator-friendly scraper/nozzle bracket to allow for the pilot to carry out the vacuuming function after scraping the ice.

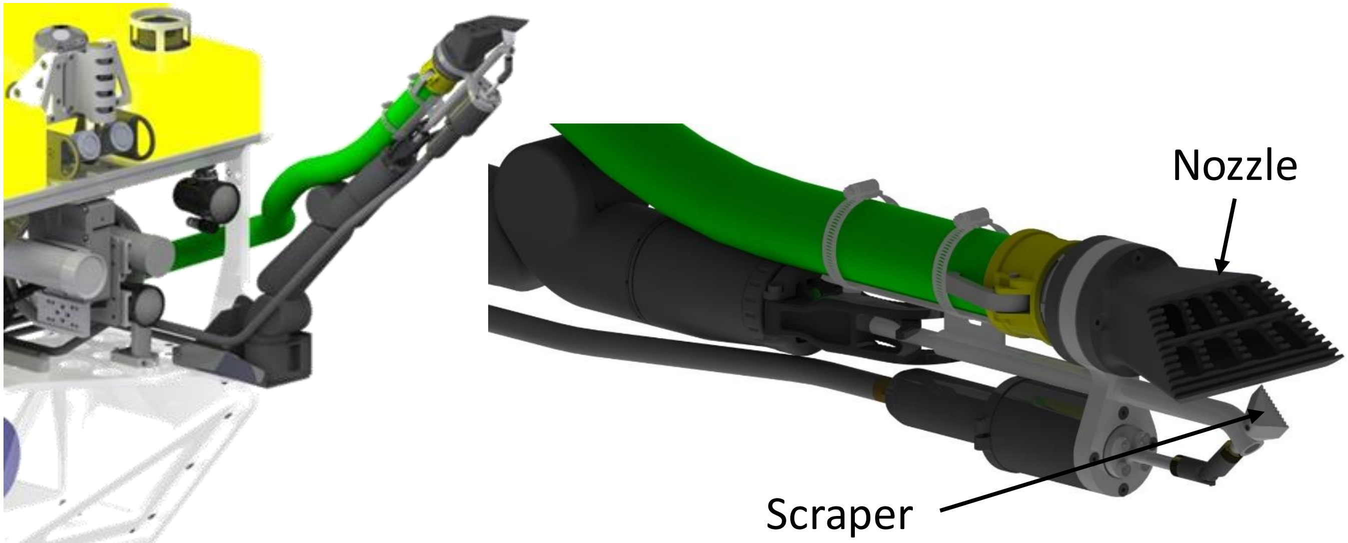

Figure 5: Rotating Scraper/Nozzle tool assembly

The suction nozzle is also shown in Figure 5. Several nozzle designs were developed, prototyped, and tested to determine the best geometric configuration to reduce the ratio of water to oil recovered. This test was performed with a lower capacity pump and hose than the ORUI system. Results are detailed in REF 4. Further refinement of the nozzle and scraper configurations are expected during the initial testing at CRREL.

The selected manipulator, as shown in Figure 6, is the Bravo 5 which is a five-function manipulator supplied by Blueprint Lab. It offers four degrees of freedom with a 26.4 lbs. full reach lift and a 44 lbs. max lift capacity. It is compatible with all the ROVs being considered in this trade study and can support the scraper assemblies.

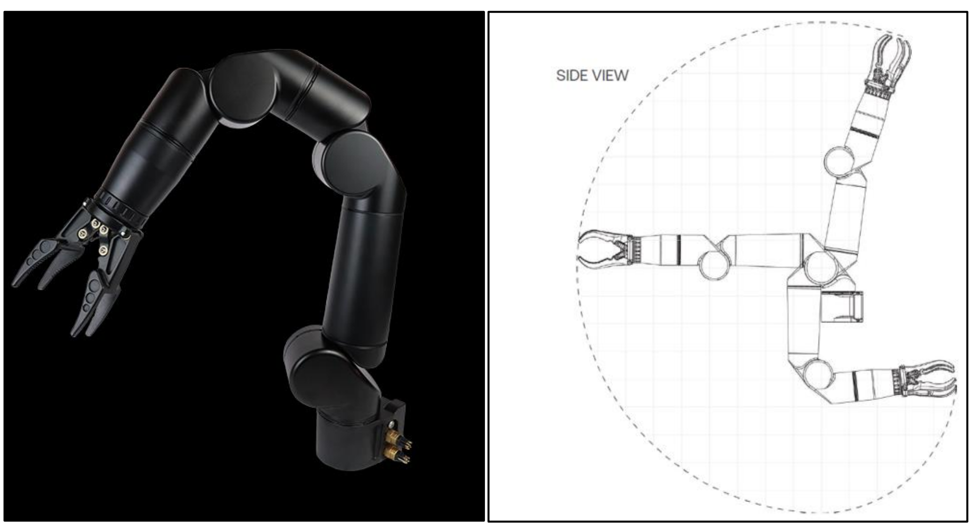

Figure 6: Bravo 5 Manipulator

The supply and integration of this manipulator on the tool skid will be performed by the selected ROV manufacturer.

5.0 TESTING AND CHARACTERIZATION

Phoenix carried out testing to verify the proper functioning of the suction nozzle, scraper assembly and imaging system lights and cameras for oil identification subsystems of the ORUI system. The main engineering verification objectives are presented in Table 1:

Test Parameter	Observation/ Reference value	Description
Suction nozzle	Observe the differences in the pump output to evaluate the nozzles being tested.	Verify which nozzle geometries allow for better oil extraction with minimal excess water.
Scraper head	Observe the difference between the oscillating scraper head and the rotary scraper head.	Verify and compare two scraper head configurations to select the better option.
Oil Detection with UV light.	Observe the differences between oil, water and ice when subjected to UV light of various wavelengths.	To evaluate the ability of UV light to assist in detecting oil within an ice-water mixture.

Table 1: ORUI Test Parameters

5.1.1 Suction Nozzle Test REF 3

The suction nozzle test is described in detail in REF 3 and is outlined below. Nine versions of the suction nozzle were generated and tested in a small-scale setup to determine geometric parameters to reduce the water to recovered oil ratio. The test setup and nozzles tested are shown in Figure 7. The test pump was a 1.5 GPM capacity, and the hose sizes were 1.5 inches compared to the designed ORUI system of 15 GPM capacity and 2 inches recovery hose diameter.

Figure 7: Suction Nozzle Test Setup (Nozzles 1-9 from left to right)

During each nozzle test a known quantity of oil was removed from the system and the run time, measured flowrate, and total volume was recorded. The run time for each nozzle was based on how long it took the nozzle to pull in the water/oil mixture. The same amount of oil (1.5 oz) was used for each run. The results of the various runs are shown in Table 2.

Nozzle	Run Time (s)	Flowrate (gal/s)	Oil Quantity (oz)	Water Quantity (gal)	Oil Transferred (oz)	Oil Transferred (gal)	Total Transferred (oil and water) (gal)	Water to oil ratio (total transferred - oil transferred) / oil transferred	RANK
1	14	0.168	1.5	5	0.8	0.00625	2.35	375	8
2	8	0.266	1.5	5	1.5	0.01172	2.13	181	1
3	13	0.181	1.5	5	1.5	0.01172	2.35	200	2
4	15	0.159	1.5	5	1.5	0.01172	2.38	202	3
5	14	0.179	1.5	5	1.35	0.01055	2.5	236	4
6	16	0.151	1.5	5	1	0.00781	2.41	307	6
7	16	0.178	1.5	5	1.25	0.00977	2.85	291	5
8	15	0.19	1.5	5	0.6	0.00469	2.85	607	9
9	20	0.14	1.5	5	1.1	0.00859	2.8	325	7

Table 2: Nozzle Experiment Results

Based on the data collected above from the nozzle runs, we were able to rank each nozzle based on a qualitative selection based on observed oil suction behavior. Nozzles 2, 3, 4 and 9 performed the best based on the least water to oil transferred ratios. It was observed during the testing that Nozzle 4 was able to draw oil from a further distance away in the test tank than the other nozzles. Based on the relative ratio and this qualitative ability to draw from a further distance Nozzle 4 was selected for further development and will provide a baseline for future refinements of the nozzle geometry.

5.1.2 Scraper Head Test REF 4

Two drive methods, oscillating and rotary, were considered for the scraper assembly. The oscillating drive was a modified commercially available DeWalt oscillating cutting tool with multiple cutter heads. The rotary scraper was based on a drill motor and a custom scraper tool. Both test scraper drives and cutters are shown in Figure 8.

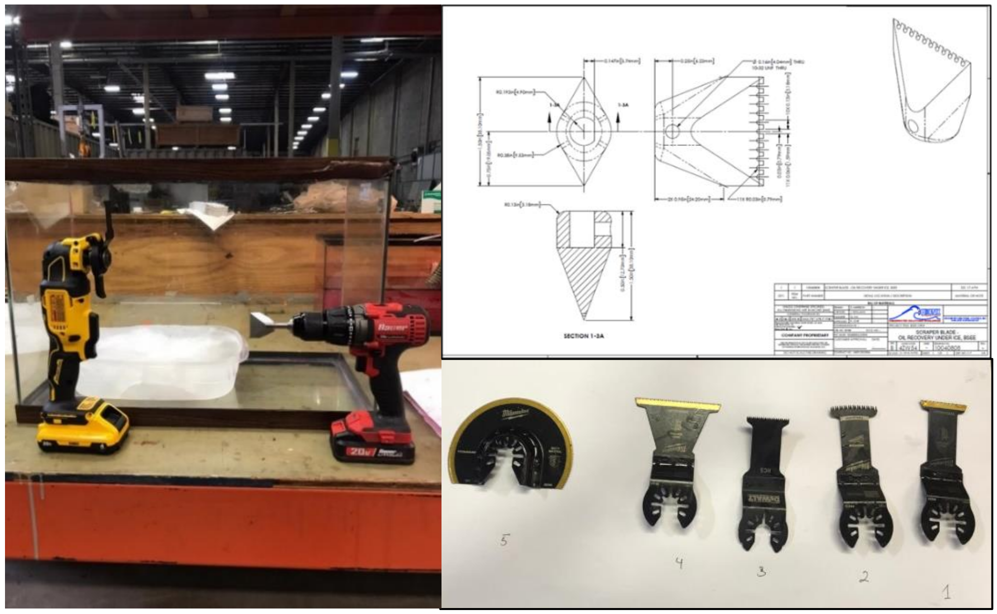

Figure 8: Oscillating (left) / Rotating (right) Scraper Drives and Various Cutters

A series of tests were performed by scraping and cutting ice blocks, as detailed in REF 4, to compare performance for both types of cutters. The rotary scraper performed significantly better by faster removal of material and a larger area of coverage per sweep. The oscillating tool required more hold down force to scrape or remove material and due to the limited stroke size of the cutter tool was much less effective at removal of sufficient material. The rotary tool was also able to effectively remove material in multiple application orientations compare to the oscillating tool. It however, required a firm grip on the drill to keep it steady especially when first starting to drill but not much downward force to get through the ice. Operation and results of the rotary scraper are shown in Figure 9.

Figure 9: Rotary Scraper Performing Cut

5.1.3 Oil Detection Test with UV Light REF 5

The oil detection test was designed to determine the performance of the ORUI imaging and oil detection system to discern UV light incident on a patch of diesel and crude oil in various lighting conditions submerged and operating underneath solid ice. The setup is shown in Figure 10.

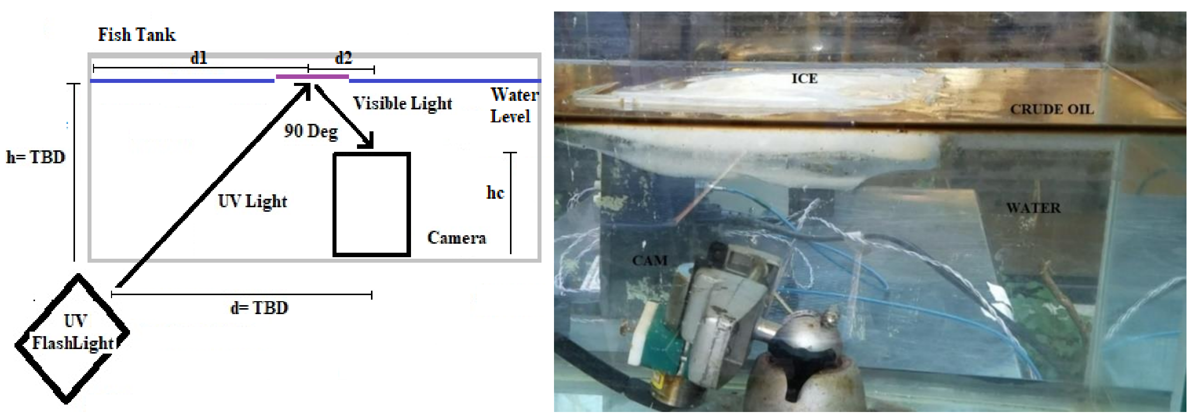

Figure 10: Oil Detection test with UV Light test setup

Figure 11: Monitor display of UV 395 nm in dark and bright surroundings (left and right images respectively)

Figure 11 shows the associated display on the monitors when 395 nm of UV light is incident on a submerged ice block with oil pockets trapped underneath. The image on the right shows the test setup done outdoors with the ambient sunlight while the left image was carried out in pitch darkness. In both cases the oil layer remains detectable by a submerged camera. This information is further described in REF 5. From these results the camera and LED floodlights of the oil imaging system were selected.

6.0 FUTURE WORK

Based on the test results to date with the prototype systems, Phoenix has identified areas for future work to ensure the system is completely reliable and commercially ready. These include:

- Evaluate topside control options and umbilical and handling system.
- Perform additional testing in more representative environmental conditions, i.e., temperatures, including ice coverage on a larger scale tank including testing with actual crude oil of various types, emulsifications and weathering and actual pump and hose sizes and capacities.
- Further nozzle refinement based on the results of the Suction Nozzle test REF 4. Testing the selected nozzle geometry with other modifications while including oil/ice crystals from scraping will give a better representation of the system's operating environment. Refinements will be investigated during interim testing at CRREL and finalized during final testing.
- More research into the scraping function from underneath the ice surface and integration tests with nozzle and pump attached.
- Positioning of the up-looking cameras can be modified depending on future experimentation.

7.0 CONCLUSION

For this project, we studied 36 ROVs and down selected to one of three options. This selected ROV (SAAB Cougar XTi) was also selected based on its ability to electrically interface with the specified pump/ motor combination. The tool skid on which the pump and motor will be secured and integrated to the ROV was also designed and analyzed structurally to ensure it survives operational environment.

To complete the ORUI system design, we also developed, selected, and tested different aspects of the ice scraper system (Nozzle and scraper) and equipment for oil imaging, detection, and navigation.

Overall, the test results obtained from development and testing of the ORUI prototype systems show it as a reliable and effective method for oil recovery under solid ice at arctic conditions.

8.0 ACKNOWLEDGEMENT

Phoenix International Holdings, Inc. acknowledges the Bureau of Safety and Environmental Enforcement (BSEE) for sponsoring this project and providing necessary guidance, discussion and support in its completion.