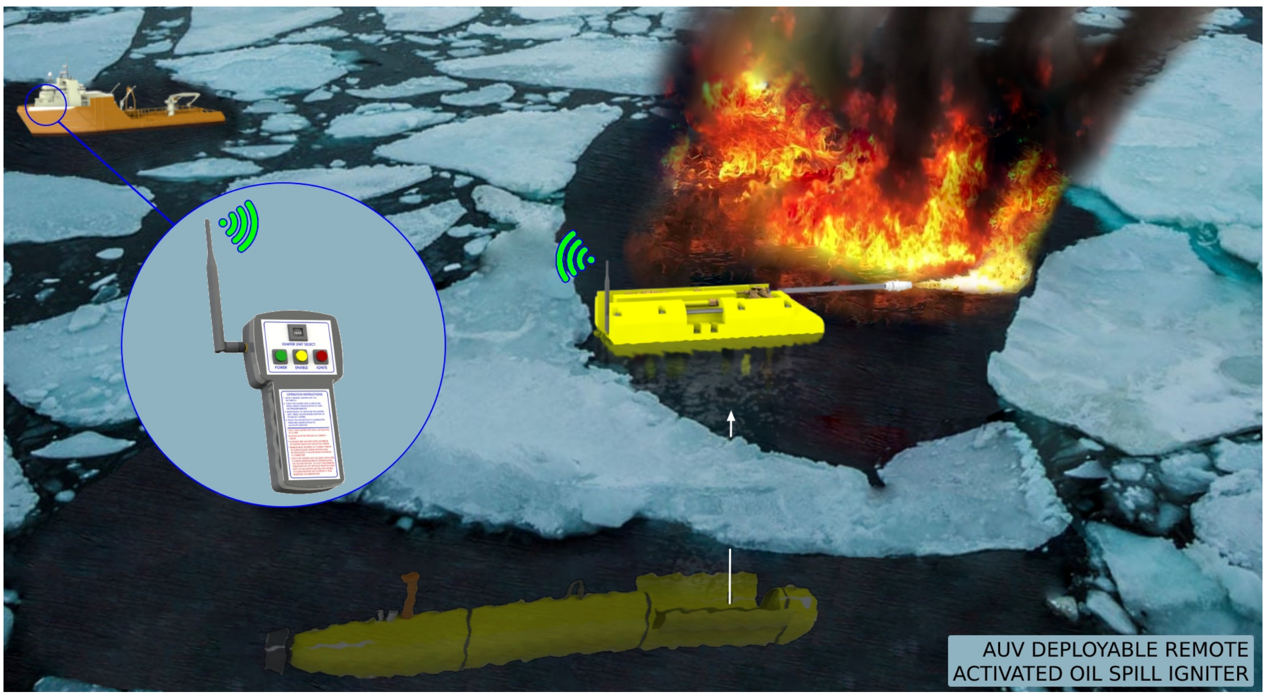
Bureau of Safety and Environmental Enforcement
Oil Spill Preparedness Division
AUTONOMOUS UNDERWATER VEHICLE DEPLOYABLE OIL SPILL IGNITER PHASE II

Final Report

September 2021



(Illustration: Phoenix International Holdings, Inc., 2021)

Clare Dowley and Robert Lohe

US Department of the Interior
Bureau of Safety and Environmental Enforcement
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Final Report

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September 2021

Authors:
Clare Dowley
Rober Lohe
Phoenix International Holdings, Inc.
9301 Largo Drive West
Largo, MD 20774

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By
Phoenix International Holdings, Inc.

US Department of the Interior
Bureau of Safety and Environmental Enforcement
Oil Spill Preparedness Division

DISCLAIMER

Study concept, oversight, and funding were provided by the US Department of the Interior (DOI), Bureau of Safety and Environmental Enforcement (BSEE), Oil Spill Preparedness Division (OSPD), Sterling, VA, under Contract Number **140E0120C0004**. This report has been technically reviewed by BSEE, and it has been approved for publication. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the US Government, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

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ABOUT THE COVER

Cover image by Phoenix International Holdings, Inc. illustrating conceptual operations of the SPORT Igniter being remotely operated in an extreme environment.

AUTONOMOUS UNDERWATER VEHICLE DEPLOYABLE OIL SPILL IGNITER PHASE II FINAL REPORT

Final Report

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For:
Karen Stone
BUREAU OF SAFETY AND ENVIRONMENTAL ENFORCEMENT (BSEE)
ACQUISITION OPERATIONS BRANCH
45600 Woodland Road, VAE-AMD
Sterling, VA 20166

September 3rd, 2021

Clare Dowley
Mechanical Engineer
cdowley@phnx-international.com

Robert Lohe
Mechanical Engineering Manager
rlohe@phnx-international.com

PHOENIX INTERNATIONAL HOLDINGS, INC.
9301 Largo Drive West
Largo, MD 20774
Phone: 301.341.7800
www.phnx-international.com

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Executive Summary

In response to Bureau of Safety and Environmental Enforcement (BSEE) solicitation 140E0119Q0063 for Research on Oil Spill Response Operations on the U.S. Outer Continental Shelf Phase II, Phoenix International Holdings, Inc. (Phoenix) has matured the Phase I ignition system design and demonstrated an underwater deployable, in-situ igniter system as well as developed the Autonomous Underwater Vehicle (AUV) Launch Module. This novel igniter system has minimized the risk of unpredicted flash fires created by combustible gasses in the atmosphere surrounding the oil spill and enabled a larger margin of safety between the response crew and the potential heat source. The preliminary AUV design has introduced more deployment opportunities for the system. The proposed Small, Portable, Oxygen-driven, Remote, Torch Phase II (SPORT PHII) igniter, has been demonstrated to be adaptable in response to the different requirements outlined in *API Technical Report 1252, Field Operations Guide for In-Situ Burning of On-Water Oil Spills [1]* in regards to simulated oil spills (using both dodecane and crude oil), the thickness of the spill, and the surrounding environmental conditions (e.g., winds, waves, ice, and current) among other considerations described in the operational guide.

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

- Upgrade of the SPORT igniter implementation into one coaxial igniter system designed to be more robust.
- Upgrade the SPORT igniter to operate using gelled diesel fuel.
- Improve upon the manufacturability of the battery modules.
- Characterization of SPORT PHII igniter functionality in controlled testing environments including:
    - Demonstration test of SPORT PHII igniter ignition of a small-scale simulated oil spill using dodecane.
    - Demonstration test of SPORT PHII igniter ignition of a small-scale simulated crude oil spill.
    - Demonstration test of SPORT PHII igniter ignition of a large-scale simulated crude oil spill.
- Design and demonstration test of an AUV deployment and release system.

This SOW 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. It also harvested the best experience gained in the field during the previous phase while advancing the technology readiness of the past proposed solutions. This approach combines proven results in a safe, economically feasible, and controllable solution to ensure results with minimum risk to human lives and the environment in the execution of an inherently dangerous activity.

Study concept, oversight, and funding were provided by the U.S. Department of the Interior, Bureau of Safety and Environmental Enforcement, Oil Spill Preparedness Division, Sterling, VA under Contract Number 140E0120C0004.

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1.0 INTRODUCTION

Phoenix International Holdings, Inc. (Phoenix) has performed the proposed worked under contract 140E0120C0004 to mature the design of the SPORT igniter into one coaxial igniter and in a submersible package, characterize the SPORT PHII igniter in multiple controlled testing environments, and demonstrate the SPORT PHII igniter ignition of a simulated oil spill. Phoenix also developed a preliminary design and prototype to demonstrate the deployment capabilities of the SPORT PHII from an AUV. The following presents a brief background of the system, introduces the SPORT PHII igniter and AUV designs, outlines the testing and characterization, and presents test results.

2.0 BACKGROUND RESEARCH ON IN-SITU BURNING OF OIL AND EXISTING TECHNOLOGIES

In-situ burning of oil spills has been studied and characterized in several papers and industry guidelines. A few key points are presented here which are applicable to the design and development of the SPORT PHII igniter.

From *Igniters and Ignition Technology for In-situ Burning of Oil Fact Sheet, U.S. National Response Team (NRT) —Science and Technology Committee, October 1995 [2]:*

"To ignite oil on water, an igniter must deliver enough heat to volatilize the hydrocarbons in the oil fast enough to maintain the vapor concentration necessary to support burning. Additional heat energy must then be provided to actually start burning the oil."

"Thus, for successful ignition, a slick must be thick enough to minimize heat dissipation and allow the surface layer near the igniter to heat above its flash point."

"The thickness necessary for ignition depends upon the type of oil and its degree of weathering: fresh, volatile crude requires a minimum thickness of 1 millimeter (mm), whereas aged, non-emulsified crude and diesel fuels require 3 to 5 mm. Other factors affecting the ignitability of oil slicks at sea include wind speed; igniter strength, heat flux, and flame duration; ambient air, oil, and water temperatures; wave action; and degree of emulsification of the oil slick (*Buist, et al., 1994*)."

"Oil can be burned on water without using containment booms if the slick is thick enough (2 to 3 mm) to ignite. For most crude oils, however, this thickness is only maintained for a few hours after the spill occurs. Oil on the open sea rapidly spreads to an equilibrium thickness, which is about 0.01 to 0.1 mm for light crude oils and about 0.05 to 0.5 mm for heavy crudes and residual oils. Such slicks are too thin to ignite and containment is required to concentrate the oil so it is thick enough to ignite and burn efficiently (*Fingas, Merv. [3])*"

"In the design of an ignition system, the rate of energy release must be balanced between two extremes. The igniter must provide enough heat energy for the vaporization and ignition of a slick. An abrupt, explosive release of energy, however, can blast the oil away from the igniter, decreasing the likelihood of ignition. Other considerations for design include safety in operation, storage, and transportation; simplicity of design and use; durability to survive free-falls (for aerial systems) from altitudes of at least 50 to 100 feet (15 to 30 meters); and reliability after long-term storage."

The following four common disadvantages have been determined and identified from evaluations of several previous system implementations of in-situ oil spill burning devices. These are covered in *Igniters and Ignition Technology for In-situ Burning of Oil Fact Sheet, U.S. National Response Team (NRT) —Science and Technology Committee, October 1995, [2]* and in the *Guidelines for the selection of in-situ burning equipment, Oil Spill Response Joint Industry Project, IPIECA/IOGP 2014, [4]*.

- Lack of reliability after long term storage above 5 years, primarily related to solid rocket fuels and 'thermite" based igniters.
- Concerns of crew and personnel safety when manipulating open flames near the oil slick site where ignitable gases and fumes may be present, including floating gel packs with marine flares, fuel impregnated rags and propane torches.
- Lack of reliability due to oil slick coating and water immersion.
- Relatively high operational cost and limited operability during adverse weather conditions (e.g., Helitorch).

3.0 SPORT PHII IGNITER DESIGN

3.1 Methodology

The SPORT PHII igniter integrates two complementary ignition systems into one coaxial delivery and control electronics in a compact module configured to be reliable and effective during in-situ oil burns at sea. Once the igniter is released, activation of the SPORT PHII igniter can be carried out remotely from a safe distance or via preprogrammed activation depending on operational requirements. The SPORT PHII igniter is considered a consumable item.

The following section defines the ignition system, exothermic rod with O2 and liquid gelled fuel. The compact SPORT PHII igniter package is presented in Figure 1.

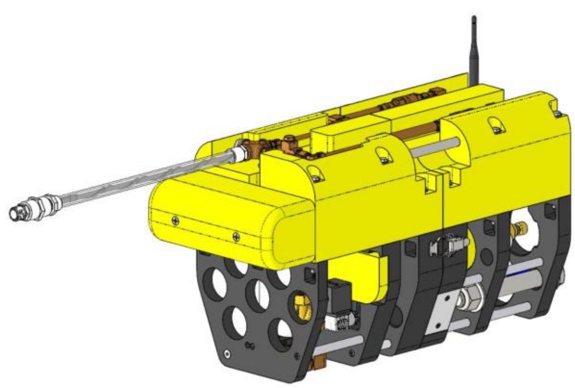

Figure 1: SPORT PHII Igniter

3.1.1 Coaxial Ignition System

The coaxial ignition system of SPORT PHII igniter is a high heat flux source to produce an un-extinguishable flux of molten metal and oxygen to ignite vapors and fuel in close vicinity of the igniter while raising the oil temperature to support burning in cold environments.

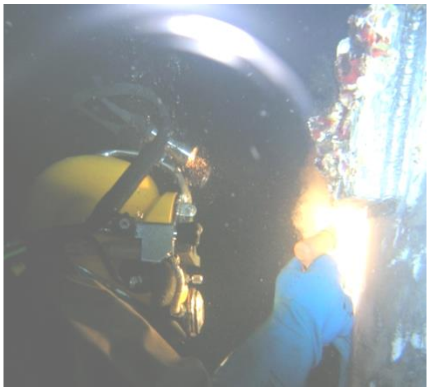

Figure 2: Phoenix Diver Performing Underwater Cutting

This high heat flux source is based on exothermic cutting rods used in underwater salvage and demolition operations. Phoenix has extensive experience using exothermic cutting devices (see Figure 2) which use an exothermic cutting rod and pure oxygen to produce extremely high temperatures.

While burning, the exothermic cutting rod is consumed which delivers extreme heat flux in the form of melted metal droplets. The burning time of the exothermic cutting rod is controlled by the pressure and flow of the oxygen from a dedicated source or canister. The flow of oxygen is set at a predetermined rate and controlled by an electronic solenoid valve and a back flash arrester to prevent ignition of the oxygen canister. The exothermic cutting rod is ignited by an electronically triggered ignition command that creates sparks within steel wool to initiate the reaction of the exothermic rod. These rods have been selected for their reliability and known capability of ignition and duration of burning while submerged. Once ignited, the exothermic rod is only extinguished by cutting off the flow of oxygen or when it is completely consumed. Almost all components of the proposed ignition system are Commercial Off-The-Shelf (COTS) components designed for reliability in the adverse environmental conditions expected for in-situ oil spill burning while providing a reliable, cost effective, high heat flux source. The coaxial igniter ignition system includes one COTS component that has been modified via machining to best connect the exothermic cutting rod to the oxygen delivery system (See Figure 3 and Figure 4).

Figure 3: Machined COTS Component

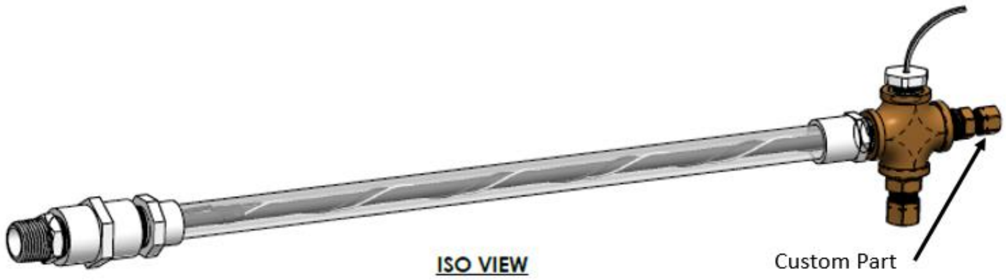

Figure 4: Location of Custom Part Within Igniter System (Part #4, Ref [5])

The second part of the coaxial ignition system is a fuel source to augment the exothermic rod by dispensing a liquid fuel, such as gelled diesel fuel. The liquid fuel is ignited as it reaches the end of the lit exothermic rod. This increases the dispersion combustion area of the igniter to increase effective temperature and burning time. The liquid fuel ignition system of the SPORT PHII igniter is composed of a reservoir of liquid fuel pressurized by a combustible gas as a propellant, such as MethylAcetylene-Propadiene Propane, or MAPP gas, to deliver the liquid fuel to the exothermic torch through the coaxial pipe. When the liquid fuel is completely dispensed, the residual volume of combustible gas propellant will continue to burn to keep high temperatures in place for additional heat flux delivery. The flow of liquid fuel is set at a predetermined rate via the MAPP gas pressure release and controlled by an electronic solenoid valve in series with a back flash arrester to prevent ignition of the liquid fuel canister or MAPP gas canister. All components of the liquid fuel ignition system are COTS components which are readily available and cost effective.

3.1.2 Control Electronics and Packaging

The operation of the SPORT PHII igniter is controlled by an integral electronic control system comprising an energy source (control battery and ignition battery), a timing and control circuit for the exothermic rod ignition heater and the control of the three system flow valves. The control circuit proposed for the SPORT PHII igniter includes programmable capabilities to trigger the SPORT PHII igniter activation from a selection of inputs including but not limited to: acoustic signals, ejection from the payload carrier, remote radio signal, etc. Phoenix used a remote activation module as shown in Figure 5. Remote activation allows the user to control initiation at a safe distance from the flames and oil itself.

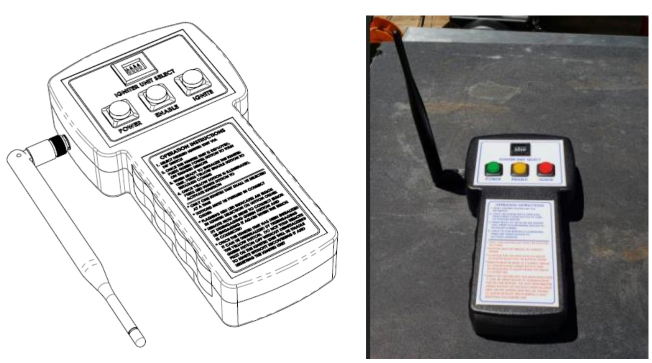

Figure 5: SPORT PHII Igniter Controller (Ref [6])

The controller system features four dip switches at the top that are programmed to each of the four electronics bottles in each of the four SPORT PHII units. The controller only works if only one dip switch is selected, this prevents the ignition of a unit that may be on standby. If two or more dip switches are selected, the system will not respond, and it will flash the Red LED.

The Green switch powers the trigger unit. The Yellow switch enables the igniter module and will light up when communications have been established with SPORT PHII. The Yellow switch will only enable if the green switch is latched. The Red switch enables the ignition process. Red switch will only enable if the green and yellow switches are latched. If an error in the sequence occurs, the red LED flashes. The Operational Distance of the remote controller was system tested at 150 yards with direct view. Further operating instructions are detailed in SPORT PHII Operational Instructions.

3.1.3 Conceptual Layout

A conceptual layout of the SPORT PHII igniter is shown in Figure 6. The red horizontal cylinder is the oxygen canister, the yellow horizontal cylinder is the MAPP canister, the black horizontal cylinder is the electronics bottle, and the silver vertical cylinder is the gelled fuel reservoir.

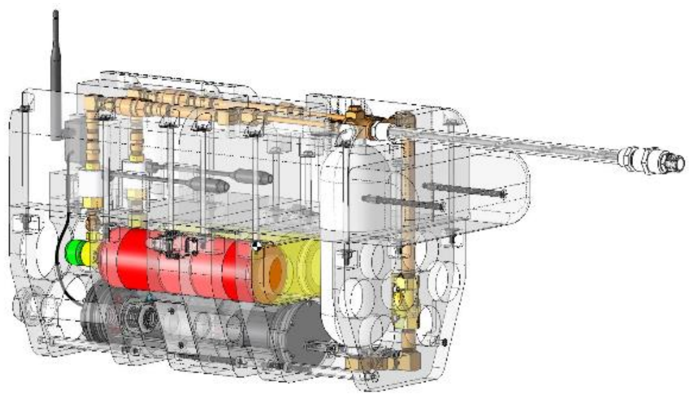

Figure 6: Conceptual Layout of SPORT PHII (Ref [7])

The buoyancy foam and Delrin framing are shown as semi-translucent around the cylinders so the interior pipelines can be better seen. The MAPP gas propels the gelled fuel through associated pipelines and meets the oxygen pipeline to flow directly into the coaxial igniter to fuel the exothermic rod consumption. A set of wires connects the electronics bottle to the coaxial igniter to deliver the ignition command and cause the sparks that when combined with the oxygen cause the exothermic rod to ignite. The electronics bottle also controls the three valves to open and close the oxygen, MAPP, and gelled fuel supplies.

In the scenario when the SPORT PHII igniter is deployed from an underwater payload, the system will float to the surface and remain oriented as shown in Figure 6. Buoyancy foam provides the proper floatation for the orientation of the exothermic torch with respect to the surface of the oil spill and the Delrin framing provides a mounting structure for the components of the system.

3.2 System Interconnection and Operational Ignition Sequence

A block diagram of the SPORT PHII igniter is shown in Figure 7 and guides the narrative of the proposed ignition system:

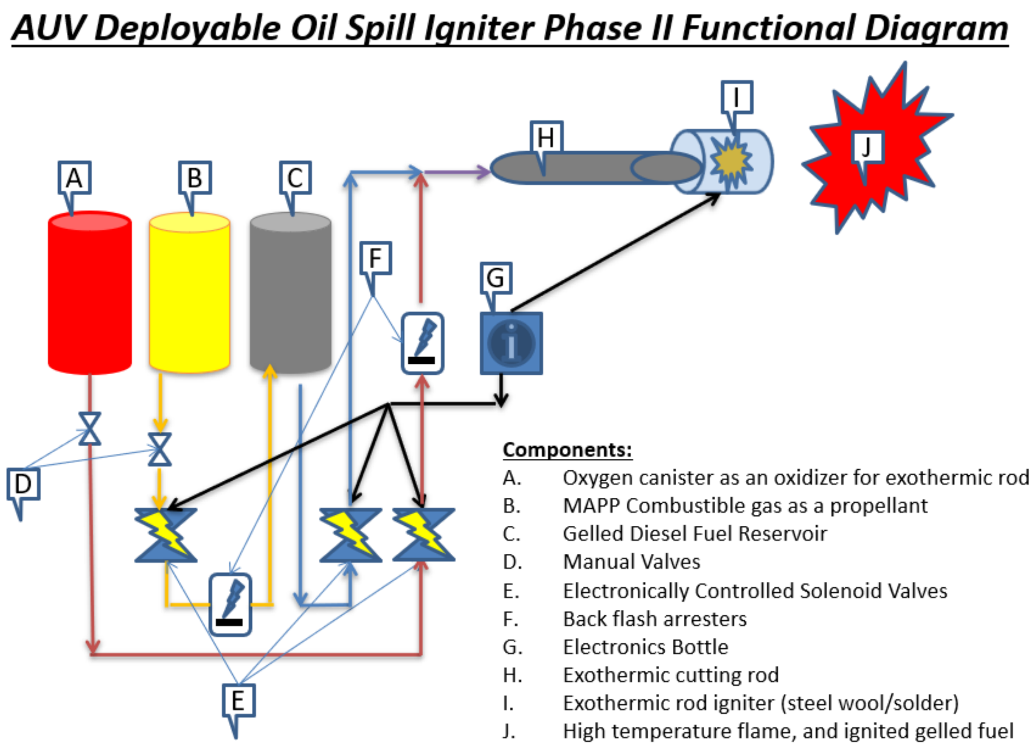

Figure 7: SPORT PHII Functional Diagram

1- Once deployed into the water inside an AUV, the SPORT PHII igniter is released and rises to the water surface due to inherent buoyancy and floats at the oil slick inside the collecting boom. Once at the desired position, the SPORT PHII igniter receives a remote activation signal, triggering the electronics bottle (G) to activate. Once activated, the solenoid valve (E) in the oxygen pipeline is opened and the pressurized oxygen starts flowing to the tip of the exothermic rod (H).
2- After a short delay that allows the oxygen sufficient time to reach the tip, the electronics bottle (G) gives the ignition command through the wires connecting the bottle and the exothermic rod igniter (I). This causes sparks within the steel wool and solder wrapping that when combined with the pressurized flow of oxygen, ignites the tip of the exothermic rod (H) creating a torch flame with temperatures above 5000 degrees F. As part of its functionality the exothermic rod (H) will be consumed.
3- After a delay to allow the exothermic rod (H) to catch, the solenoid valves (E) in both the MAPP and the gelled fuel pipelines are opened. The pressurized MAPP gas propels the gelled fuel through the pipelines until meeting the oxygen flow and the ignited tip of the exothermic rod. The gelled fuel mixture ignites upon contact with the lit exothermic rod. The burning fuel disperses on top of the oil slick in contact with water, providing sustained burning time and heat at the air/oil interface. This initiates ignition of the combustible gases and film of the oil slick to enable self-sustained oil spill burning.

4- When the gelled fuel (from cylinder C) has been completely dispensed, the residual combustible propellant gas from cylinder B continues to fuel the burn, ensuring a high temperature flame out of the nozzle to keep the surrounding atmosphere at ignition temperature.

5- Once all liquid fuel (C), propellant gas (B) and oxygen (A) are depleted, the igniter system shuts off and continues to float inside the fireproof boom. At this time, the ignition burn is completed, the oil spill is burning, and the SPORT PHII igniter can be recovered for disposal or abandoned on site.

4.0 AUTONOMOUS UNDERWATER VEHICLE (AUV) DEPLOYMENT

4.1 Methodology

In Phase II, Phoenix evaluated the feasibility and integration to an Autonomous Underwater Vehicle (AUV) payload system and developed a preliminary test AUV launch module to simulate the release of the SPORT PHII from beneath an oil/ice test environment. This deployment concept was then demonstrated in a simulated control scenario.

4.2 Release Mechanism

The AUV mockup uses electromagnets to hold SPORT PHII in position inside the module and then release and allow the system to rise to the surface in the oil spill. Each SPORT PHII assembly includes two metal plates, one port and one starboard, that make the connection with the magnets inside the AUV launch mockup. A section view of the SPORT PHII is seen in Figure 8 showing the plates. Figure 9 details the magnets inside the AUV mockup.

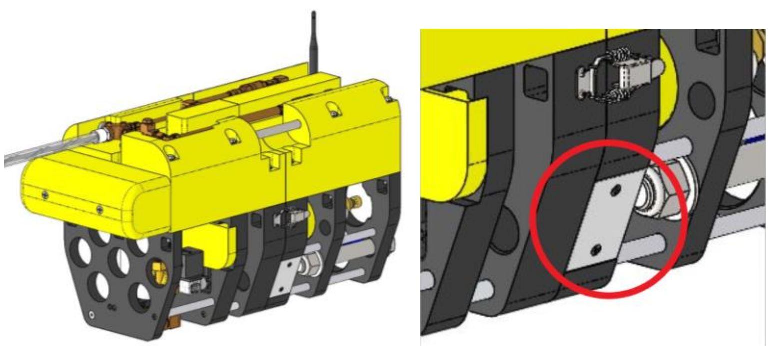

Figure 8: Metal Plates on SPORT PHII for AUV Connection

Figure 9: Electromagnets Mounted Inside AUV Mockup Cradle to Hold SPORT PHII

4.3 Conceptual Layout

The AUV mockup design includes a tube-like section with a cradle inside to hold the SPORT PHII. The tube section has two doors topside that swing open prior to the electromagnet release that the system exits through to float to the surface. The doors are held shut via another set of electromagnets, and once released are pulled open by bungee cords. Based primarily on the weight of the AUV mockup doors and the pressure of the water at depth, the strength needed in the bungee cords was calculated such that the doors will swing open easily upon magnet release *[8]*. Due to restrictions described in section 4.4, two concept layouts were created and can be seen in Figure 10 and Figure 11.

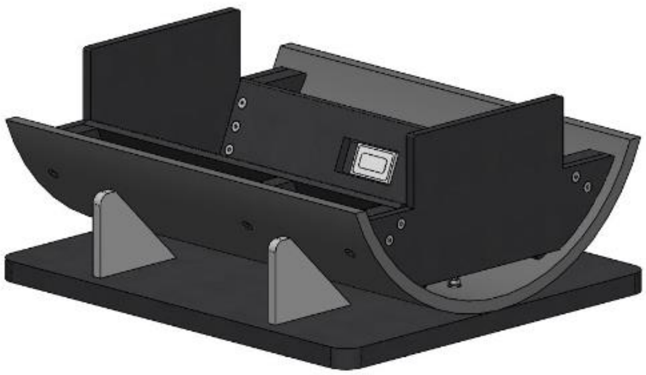

Figure 10: Simplified AUV Launch Module Concept Layout (Ref [9])

Figure 11: Full-Scale AUV Launch Module Concept Layout (Ref [10])

The AUV launch module is controlled remotely via a wired connection. The test module is hardwired for control from the surface for test purposes due to the test schedule and preparation times. The controller, seen in Figure 12, includes a release for both the electromagnets holding the doors closed as well as the electromagnets holding SPORT PHII inside the cradle.

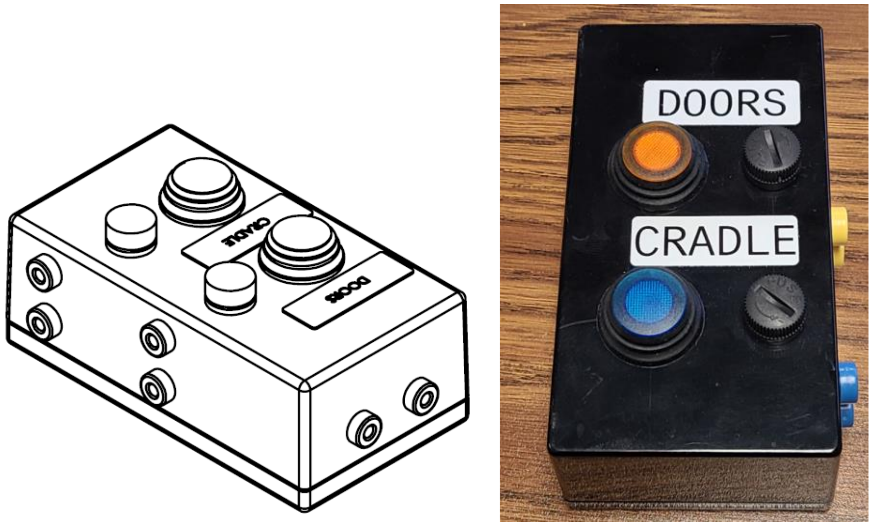

Figure 12: AUV Launch Module Controller (Ref [11])

4.4 Prototypes

Two prototypes of the AUV launch module were built due to test location restrictions. The size of SPORT PHII dictates the size of the cradle. For preliminary on-site testing, the burn tank was not large enough to accommodate the full-scale AUV launch module with doors. A simplified mockup was constructed that only included the interior cradle and electromagnet release mechanism so that the release could be demonstrated simultaneously with SPORT PHII burn performance. This tested the AUV launch module release mechanism in most of the same environmental conditions the SPORT PHII is required to meet. The simplified mockup is shown in Figure 13.

Figure 13: Simplified AUV Launch Module Prototype

A larger tank was available to test the AUV mockup but was not available for burn testing. As testing with oil was not required for AUV testing, the full-scale AUV launch module including the hinged doors was constructed and the release of SPORT PHII was tested without a consecutive burn. The full-scale mockup is shown in Figure 14.

Figure 14: Full-Scale AUV Launch Module Prototype

5.0 TEST DESCRIPTIONS AND CHARACTERIZATION

Phoenix has adopted the following guidelines for SPORT PHII igniter field qualification testing parameters as the target requirements. These are as prescribed in the *Field Operations Guide for In-Situ Burning of On-Water Oil Spills ((API) Technical Report 1252 [1])* and the limiting factors discussed in *Oil Spill - Behavior, Response and Planning, Open-water Response Strategies: In-situ Burning*; *[12]*. Table 1 presents the target parameters from the Phase II contract.

Table 1: SPORT PHII Igniter Test Parameters

Test Parameter	Reference Value	Description
Winds	Up to 18 knots	Testing for ignition and sustained burning in higher wind conditions.
Wave Height	Choppy waves to the test facilities' capabilities	Testing for stability of igniter position and functionality to determine the sea state at which the ignition system and AUV can operate.
Current	0.75 to 1 knot	Towing velocity of the fire boom in which *in situ* burning operations are conducted.
Oil Type	ANS and HOOPS	To test for ignitability with different types of oil for the CRREL tests.
Oil Thickness	Greater than 3mm	Test for ignition time.
Weathering and Emulsification	Weathered oil and emulsifications of 25% - 40% water content.	In addition to testing with fresh, neat oil, testing the ignitability of weathered and emulsified crude oil, which shall require high heat flux and sustained heating area is required.
Ice	10% to 20% coverage and frazil ice.	Testing for deploy ability and temperature effects on igniter.
AUV Deployable	Stationary AUV payload module	Vehicle to be deployable by AUV

At certain stages of the project the test parameters were reduced due to availability of the permits required to perform burns on the various oil types and emulsifications.

To verify the functionality of the system and verify full compliance to the proposed system specifications for the remote system activation, exothermic reaction delivery system (exothermic cutting rod) and accelerant fuel delivery (fuel and combustible gas) the prototype igniters were subject to several internal engineering qualification tests prior to the following detailed field tests. The following engineering verification objectives were checked in house prior to embarking on each set of demonstration tests:

1. Verification of the specifications and capacity assumptions for the components of the igniter.
2. Verification of the functionality of the sub systems including the O2/exothermic rod circuit, the gelled fuel dispensing circuit, and the electronic ignition system independently from each other.
3. Evaluation of the functionality of the remote triggering system.
4. Verification of the full functionality of sub-systems as an integrated system, including the dimensional verification of the assembly and weight and buoyancy estimates.

Four (4) SPORT PHII igniter test units were built and subjected to the following tests and demonstrations which entail increasing levels of detail and characterization.

5.1 Phoenix Largo Facility Field Testing

The purpose of testing at the Phoenix Largo facility was to demonstrate the initial capabilities of SPORT PHII to perform in various environmental conditions, these tests were conducted to meet preliminary customer acceptance criteria to validate SPORT PHII to move on to larger scale testing. Due to permit restrictions, Dodecane was used as an oil simulant and was substituted in the demonstration tests that took place at the Phoenix facility. Additionally, due to the available technology and the burn tank size, the parameters for the environmental conditions were slightly reduced.

Full system burn duration was not able to be determined at this stage due to test tank size and the desire to keep the buoyancy foam on SPORT PHII relatively intact. Allowing a full duration burn would damage the buoyancy foam and affect the weight and balance of SPORT PHII for future testing. The simplified AUV mockup detailed previously was used at the Phoenix facility due to tank size to simulate release from an AUV prior to burn testing. The full-scale AUV mockup was tested at the Phoenix facility in a larger tank with no burn. The test matrix for Phoenix Demonstration testing is shown in Table 2 *[13]*. Test results are detailed in section 6.1.

Table 2: Phoenix Largo Facility Test Matrix

Burn Event	Test #1	Test #2	Test #3	Test #4
Winds	X			
Wave Height		X		
Current			X	
Ice (Frazil)				X
Oil Thickness	X	X	X	X
AUV Deployable	X	X	X	X

The customer acceptance and Phoenix demonstration test parameters included the following test scenarios:

1. Wind Test - The wind test is to determine the igniter operation in wind conditions up to the test parameter speeds, 18 knots. These wind speeds were attained by a high velocity fan set up next to the tank, shown in Figure 15.

Figure 15: Dodecane Wind Burn at Phoenix Facility

2. Wave Test: This test characterizes the ability of the system to ignite and burn in various orientations and motions of simulated wave action. Due to the available technology and the size of the tank, the generated waves did not reach the desired parameters but were as large as possible in the given conditions. Figure 16 shows the Dodecane ignition in wave conditions.

Figure 16: Dodecane Wave Burn at Phoenix Facility

3. Current Test: This test demonstrated the capability of the igniter to perform in a moving water field. Current was generated by a water circulator placed on the floor of the tank. Figure 17 shows the Dodecane ignition by the SPORT PHII in the current.

Figure 17: Dodecane Current Burn at Phoenix Facility

4. Ice Test – The ice test provides a 20-30% coverage of frazil ice and lowers the water and Dodecane temperature during the test. Figure 18 shows Dodecane ignition after SPORT PHII surfaced with ice coverage.

Figure 18: Dodecane Ice Burn at Phoenix Facility

5. Simplified AUV Mockup Test – This test shows that SPORT PHII can be released from the AUV and subsequently complete a burn. Figure 19 shows SPORT PHII inside and then surfaced from the simplified AUV Mockup.

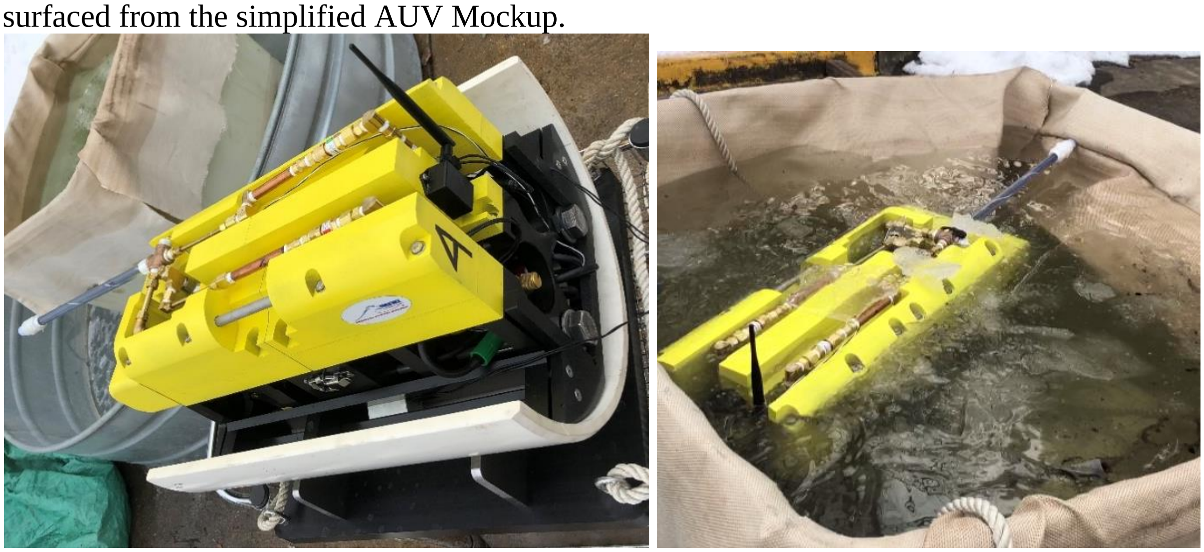

Figure 19: Simplified AUV Mockup Test

6. Full-Scale AUV Mockup Test – This test shows that SPORT PHII can be released from the full-scale AUV mockup after the doors were successfully released and opened. Figure 20 shows SPORT PHII inside and then surfaced from the full-scale AUV mockup.

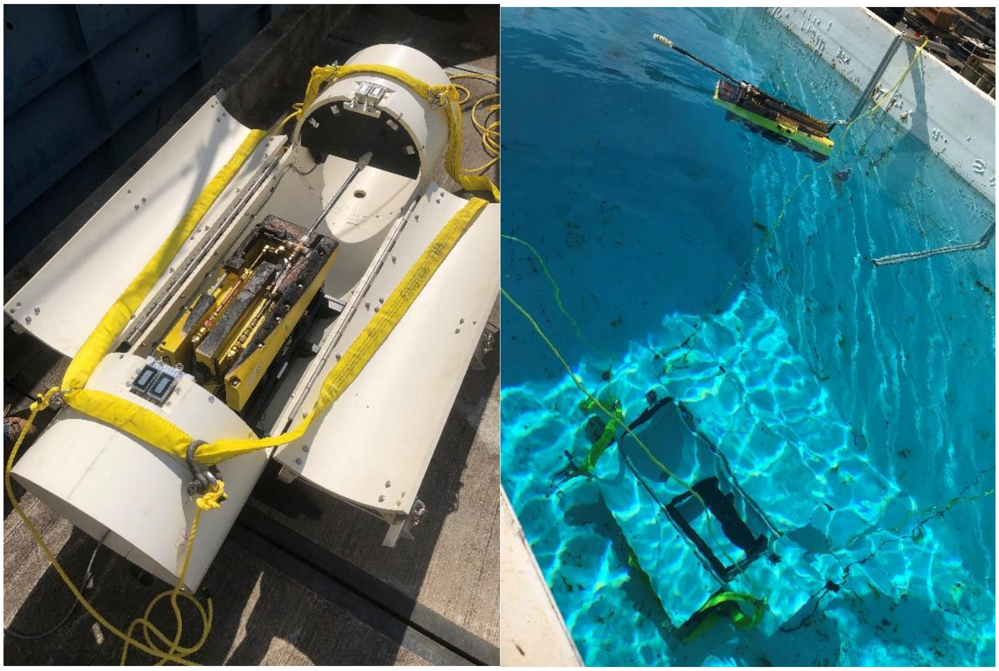

Figure 20: Full-Scale AUV Mockup Test

5.2 Maryland Fire and Rescue Institute (MFRI) Field Testing

The purpose for testing at MFRI was to demonstrate that the SPORT PHII could ignite crude oil on a small-scale prior to moving to large-scale testing. Some HOOPS was left neat and some was emulsified with approximately 30% water content for the tests. Tests completed were Quiescent, no other environmental conditions were tested at this location. This is the basic characterization test to determine the baseline performance of the system.

Full system burn duration was not able to be determined at this stage due to test tank size and the desire to keep the buoyancy foam on SPORT PHII relatively intact. Allowing a full duration burn would damage the buoyancy foam and affect the weight and balance of SPORT PHII for future testing. The simplified AUV mockup detailed previously was used at MFRI due to tank size to simulate release from an AUV prior to burn testing. The test matrix for MFRI demonstration testing is shown in Table 3 *[14]*. Figure 21 shows crude oil ignition at the MFRI facility. Test results are detailed in section 6.2.

Table 3: MFRI Test Matrix

Burn Event	Test #1	Test #2	Test #3	Test #4	Test #5	Test #6
Oil Type: Neat HOOPS	X	X				
Oil Type: Emulsified HOOPS			X	X	X	X
Oil Thickness	X	X	X	X	X	X
AUV Deployable	X	X	X	X	X	X

Figure 21: Quiescent HOOPS Burn at MFRI Facility

5.3 Cold Regions Research and Engineering Laboratory (CRREL) Field Testing

The purpose for testing at CRREL was to demonstrate that SPORT PHII could ignite large-scale crude oil spills in various environmental conditions. The CRREL facility has a large burn tank with the ability to simulate many conditions that could be seen in real oil spill scenarios. Due to shipping and transport restrictions, it was determined that AUV deploy ability would not be tested at CRREL using the full-scale AUV mockup despite the availability of a larger tank. Release from sub-surface prior to burn initiation was instead simulated via a pulley method inside the test tank.

The test matrix for CRREL demonstration testing is shown in Table 4 *[15]*. It should be noted that only one of the oil types was used for each test and that duplicates of each test listed below may have also been performed, as well as tests with combinations of environmental conditions. Test results are detailed in section 6.3 and the CRREL test matrix only details the minimum of parameters that were to be tested. Figure 22 shows an example of a crude oil burn at CRREL.

Table 4: CRREL Test Matrix

Burn Event	Test #1	Test #2	Test #3	Test #4	Test #5	Test #6
Quiescent	X					
Frazil Ice		X				
Broken Ice			X			
Wave Height				X		
Winds					X	
Current						X
Oil Type: Weathered HOOPS	X	X	X	X	X	X
Oil Type: Weathered Emulsified HOOPS	X	X	X	X	X	X
Oil Thickness	X	X	X	X	X	X

Figure 22: Frazil Ice Weathered HOOPS Burn at CRREL

6.0 TEST RESULTS

6.1 Phoenix Largo Facility Demonstration Results

Test results for the Phoenix Demonstration / Customer Approval Tests were recorded per the tables provided in the test plan *[13]*. It should be noted that the "Dodecane Simulant Burn Off" time is not accurate as to how long it would take to entirely clean up the spill as the burns were ended via a fire extinguisher early so as not to damage the foam on the SPORT PHII to preserve it for future on-site testing.

Table 5 details the test results from the Phoenix Demonstrations. The "Observations" have been removed for ease of reading and can be found in the full table in Appendix A. Table 6 details the average time data for rod consumption, gelled fuel flow, and dodecane burn. Table 7 details the pass/fail rate of the tests conducted at the Phoenix facility. Table 8 details the objectives that were met during the Phoenix demonstrations. During this test period each unit was tested and subsequently refurbished and made ready to be retested. Refurbishment includes replacement of the exothermic cutting rod and associated housing, installation of new oxygen (O2) and MAPP gas cylinders, replacement of batteries inside the electronics bottle, and a limited deck check for functionality of the system.

Table 5: Phoenix Test Parameters and Results

Test #	Burn Event	Evaluating Parameters	Unit #	Burn Times (seconds)				
				Rod Consumption	Liquid Fuel Flowing	Dodecane Simulant Burn Off	Observations	Test Video (Filename)
1	Ice	~20-30% Frazil Ice Coverage 3mm Oil Thickness AUV Deployable	4	45 sec	37 sec	22 sec	See Appendix	"Unit 4 Ice Dodecane Burn.MOV"
2	Current	Water Velocity 0.75 – 1.0 knots 3mm Oil Thickness AUV Deployable	3	N/A	N/A	N/A	See Appendix	"Unit 3 – AUV Release – No Ignition.MOV"
3	Current	Water Velocity 0.75 – 1.0 knots 3mm Oil Thickness AUV Deployable	3	N/A	N/A	N/A	See Appendix	"Unit 3 – AUV Release – No Ignition 2.MOV"
4	Wind	Wind Speed ~16 knots 3mm Oil Thickness AUV Deployable	1	49 sec	74 sec	60 sec	See Appendix	"Unit 1 Dodecane Wind Burn.MOV"
5	Current	Water Velocity 0.75 – 1.0 knots 3mm Oil Thickness AUV Deployable	2	N/A	N/A	N/A	See Appendix	"Current – No Ignition Stalled AUV Release.MOV"
6	Current	Water Velocity 0.75 – 1.0 knots	2	N/A	N/A	N/A	See Appendix	"Current – No AUV No

		3mm Oil Thickness AUV Deployable						Ignition.MOV”
7	Current	Water Velocity 0.75 – 1.0 knots 3mm Oil Thickness AUV Deployable	2	35 sec	35 sec	38 sec	See Appendix	“Unit 2 Current Dodecane Burn. MOV”
8	Wave	Wave Height ~10 inches 3mm Oil Thickness AUV Deployable	3	55 sec	47 sec	23 sec	See Appendix	“Unit 3 Wave Dodecane Burn.MOV”

Table 6: Phoenix Test Result Averages

	Exothermic Rod Burn Time (secs)	Liquid Fuel Flowing (secs)	Dodecane Burn Time (secs)
Calculated Average from Table 5.	46 sec	48.25 sec	35.75 sec

Table 7: Simplified Phoenix Tests Results

	Total	Percentage of Total
Tests Performed at Phoenix	8	
Successful Tests	4	50%
Failed Tests	4	50%

Table 8: Phoenix Demonstration Verification Objectives

Objective	Pass	Fail	Observations
Demonstrate the basic capability of ignition of small amounts of simulated crude oil	X		Dodecane used as simulant for crude oil. SPORT PHII ignited the dodecane successfully multiple times.
Demonstrate the ability to burn simulated oil in wind, wave, current, and ice conditions.	X		SPORT PHII ignited the dodecane in each of the given environmental conditions.
Demonstrate the ability to deploy the igniter from an AUV mockup.	X		SPORT PHII was successfully released from the simplified AUV mockup prior to burn initiation.

6.1.1 Phoenix Largo Facility Demonstration Observations

During the demonstration tests at the Phoenix Largo facility, SPORT PHII met all verification criteria. Dodecane, a simulant for crude oil, was routinely ignited using the SPORT PHII coaxial ignition system. The surface of the tank would consistently catch at an average of 27.5 seconds after SPORT PHII was activated. While the burn times to completely burn off the dodecane on the surface of the tank were not able to be recorded to preserve the buoyancy foam it was noted that once lit, the dodecane would consistently continue to burn even after SPORT PHII was powered down and was no longer supplying oxygen, gelled fuel, or MAPP gas.

Due to the available test equipment and tank size, some environmental parameters were slightly scaled down at this location. However, SPORT PHII was able to light the dodecane on the surface of the tank in all ice, wind, current, and wave conditions into which it was placed.

Per Table 7, 50% of the tests conducted at the Phoenix facility were non-ignitions. Further details about these tests can be seen in Appendix A. Of the four non-ignition tests, all four were observed to have gelled fuel flow but no broco rod ignition. No sparks occurred prior to gelled fuel flow. This is standard behavior for a broco rod that has gone bad or is deemed a "dud", as was learned in initial system testing completed prior to full unit assembly. Further investigation into the working life of these exothermic cutting rods and the ability to sit on the shelf prior to deployment is needed and is listed in section 7 as future work. In all four failed tests, current was the variable being tested. Due to the small tank size available at Phoenix, each time SPORT PHII was surfaced from the simplified AUV mockup it was caught on the fire blanket that was placed on the edges of the tank to protect its structural integrity. With the current circulating, the blanket was billowed out and took up enough of the tank surface that SPORT PHII could not surface without a portion being caught in the blanket. This catch could potentially have caused the igniter to jerk and the wires to be disconnected, rendering the ignition command unable to reach the tip of the exothermic rod and sparks to be created.

6.2 MFRI Demonstration Results

Test results for the MFRI demonstration were recorded per the tables provided in the test plan *[14]*. It should be noted that the "Crude Oil Burn Off" time is not accurate as to how long it would take to entirely clean up the spill as the burns were ended via a fire extinguisher early so as not to damage the foam on the SPORT PHII to preserve it for future on-site testing as well as prevent structural damage to the burn tank to ensure it would not fail and spill fire and crude oil into the test environment.

Table 9 details the test results from the MFRI Demonstrations. The "Observations" have been removed for ease of reading and can be found in the full table in Appendix B. Table 10 details the average time data for rod consumption, gelled fuel flow, and HOOPS burn. Table 11 details the pass/fail rate of the tests conducted at MFRI. Table 12 details the objectives that were met during the MFRI demonstrations. During this test period each unit was tested and subsequently refurbished and made ready to be retested. Refurbishment includes replacement of the exothermic cutting rod and associated housing, installation of new oxygen (O2) and MAPP gas cylinders, replacement of batteries inside the electronics bottle, and a limited deck check for functionality of the system.

Table 9: MFRI Test Parameters and Results

Test #	Oil Type	Burn Times (seconds)				
		Rod Consumption	Liquid Fuel Flowing	Crude Oil Burn Off	Observations	Test Video (Filename)
1	Neat	22 sec	38 sec	33 sec	See Appendix	“IMG_9236.MOV”
2	Neat	47 sec	37 sec	26 sec	See Appendix	“IMG_9238.MOV”
3	Emulsified	46 sec	39 sec	23 sec	See Appendix	“20210302_121802.mp4”
4	Emulsified	N/A	N/A	N/A	See Appendix	“IMG_9241.MOV”
5	Emulsified	34 sec	27 sec	42 sec	See Appendix	“20210302_144111.mp4”
6	Emulsified	25 sec	20 sec	11 sec	See Appendix	“20210303_085233.mp4”
7	Emulsified	28 sec	22 sec	15 sec	See Appendix	“20210303_092222.mp4”

Table 10: MFRI Test Result Averages

	Exothermic Rod Burn Time (secs)	Liquid Fuel Flowing (secs)	Crude Oil Burn Time (secs)
Calculated Average from Table 9.	33.67 sec	30.5 sec	25 sec

Table 11: Simplified MFRI Results

	Total	Percentage of Total
Tests Performed at MFRI	7	
Successful Tests	6	86%
Failed Tests	1	14%

Table 12: MFRI Demonstration Verification Objectives

Objective	Pass	Fail	Observations
Demonstrate the basic capability of ignition of small amounts of crude oil	X		HOOPS on the test tank surface was consistently ignited.
Demonstrate the ability to burn neat and emulsified crude oil.	X		Both neat and emulsified HOOPS caught and continued to burn using SPORT PHII ignition system.
Demonstrate the ability to deploy the igniter from an AUV mockup.	X		SPORT PHII was successfully deployed from the simplified AUV mockup for the first test, then it was deemed unnecessary to launch for each test to expedite the test timeline.

6.2.1 MFRI Demonstration Observations

During the demonstration tests at the MFRI facility, SPORT PHII met all verification criteria. HOOPS, a type of crude oil, was consistently ignited in both neat and 30% water content emulsified conditions using the SPORT PHII coaxial ignition system. The surface of the tank would consistently catch at an average of 20 seconds after SPORT PHII was activated. While the burn times to completely burn off the crude oil on the surface of the tank were not able to be recorded to preserve the buoyancy foam and the test tank integrity it was noted that once lit, the crude would consistently continue to burn even after SPORT PHII was powered down and was no longer supplying oxygen, gelled fuel, or MAPP gas.

While no environmental conditions were specifically tested at this location, it was noted that the first day of testing was incredibly windy. While at times the crude oil on the surface took slightly longer to catch as the wind was directing the flames away from the tank surface, SPORT PHII was able to successfully light the surface in all tests.

Per Table 11, 14% of the tests conducted at MFRI were non-ignitions. Further details about this test can be seen in Appendix B. The one non-ignition test was observed to have gelled fuel flow but no broco rod ignition. No sparks occurred prior to gelled fuel flow. This is standard behavior for a broco rod that has gone bad or is deemed a "dud", as was learned in initial system testing completed prior to full unit assembly. Further investigation into the working life of these exothermic cutting rods and the ability to sit on the shelf prior to deployment is needed and is listed in section 7 as future work.

6.3 CRREL Demonstration Results

Test results for the CRREL demonstration were recorded per the tables provided in the test plan *[15]*. It was decided on site that the wind variable would not be tested.

Prior to each environmental condition being tested using SPORT PHII, the same conditions were tested via attempting to light the spill with a butane torch to obtain baseline control data. At times, the butane torch failed to light the spill. Where successfully ignited, the baseline control data can be utilized as a comparison to the SPORT PHII performance. Due to the large quantity of tests performed at the CRREL facility, only a portion of the test results are shown in the following tables. The excerpt details one of each environmental condition listed in the test matrix, one combination test, and varying oil types. The full table of results for both control and SPORT PHII can be seen in Appendix C. Baseline control test data is shown in Table 13 and results using SPORT PHII are shown in Table 14. For ease of comparison, similar excerpts of test parameter results are shown in both tables. “Observations” can be found in the full table in Appendix C.

The crude is considered “ignited” when it remains lit for approximately 15 seconds and when the flames start to spread. The crude is considered “caught” when the flames have spread and the fire begins to fully engulf the slick. At times, the crude would ignite but only portions would burn instead of the surface being fully engulfed. In these instances, “Time to Catch” is listed as “Was Not Achieved”. Ignition, catch, and total burn times were determined via signals given from the CRREL team.

Table 15 and Table 16 detail the average time data for ignition, catch, HOOPS burn, and system run length for the baseline control tests and the tests conducted with SPORT PHII. Table 17 details the pass/fail rate of the baseline tests conducted at CRREL and Table 18 details the pass/fail rate of the SPORT PHII tests conducted. Table 19 details the objectives that were met during the CRREL demonstrations. During this test period each unit was tested and subsequently refurbished and made ready to be retested. Refurbishment includes replacement of the exothermic cutting rod and associated housing, installation of new oxygen (O2) and MAPP gas cylinders, replacement of batteries inside the electronics bottle, and a limited deck check for functionality of the system.

Table 13: CRREL Test Parameters and Results – Baseline Control

Burn Event/Test Variable(s)	Evaluating Parameters	Test #	Time (seconds)						
			Time to Ignition	Time to Catch	Burn Length	System Run Length	Temp* (°C)	Observations	Test Video (Filename)
Quiescent & Weathered Emulsified Crude oil	Baseline	1	N/A	N/A	N/A	154.76 sec	22 (On Boom)	See Appendix	“GP031072 .MP4”
Broken Ice & Weathered Emulsified Crude Oil	20-30% Ice Coverage	6	N/A	N/A	N/A	94.31 sec	7	See Appendix	“GOPR010 1.MP4”
Frazil Ice & Weathered Crude Oil	20-30% Ice Coverage	14	63.9 sec	Was Not Achiev ed	365.72 sec	429 sec	600	See Appendix	“IMG_932 1.MOV”
Wind	No less than 18 knots.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Current & Weathered	~0.8 ft/sec	17	N/A	N/A	N/A	114 sec	28	See Appendix	“IMG_933 4.MOV”

Emulsified Crude Oil									
Wave Height & Weathered Crude Oil	~10 cm wave height, 1 sec period	11	68.33 sec	Was Not Achieved	120.81 sec	189 sec	20	See Appendix	"IMG_9308.MOV"
Current & Broken Ice & Weathered Emulsified Crude Oil	0.8 ft/sec current, 20-30% broken ice coverage	22	N/A	N/A	N/A	83 sec	33	See Appendix	"IMG_9352.MOV"

*Temperature is surface temperature unless otherwise noted. Average temperature during burn duration used. Temperature data recorded by CRREL.

Table 14: CRREL Test Parameters and Results – SPORT PHII

Burn Event/Test Variable(s)	Evaluating Parameters	Test #	Time (seconds)				Temp* (°C)	Observations	Test Video (Filename)
			Time to Ignition	Time to Catch	Burn Length	System Run Length			
Quiescent & Weathered Emulsified Crude oil	Baseline	4	37.63 sec	30.83 sec	453.84 sec	491.49 sec	600 (In Flame)	See Appendix	"GOPR0033.MP4" and "GP020098.MP4"
Broken Ice & Weathered Crude Oil	20-30% Ice Coverage	16	32 sec	39.53 sec	325.53 sec	360 sec	400	See Appendix	"IMG_9330.MOV"
Frazil Ice & Weathered Crude Oil	20-30% Ice Coverage	13	32.46 sec	142.97 sec	228.97 sec	262 sec	480	See Appendix	"IMG_9318.MOV"
Wind	No less than 18 knots.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Current & Weathered Emulsified Crude Oil	~0.8 ft/sec	20	47.77 sec	104.85 sec	440.85 sec	489 sec	450	See Appendix	"IMG_9344.MOV"
Wave Height & Weathered Crude Oil	~10 cm wave height, 1 sec period	12	51.87 sec	Was Not Achieved	406 sec	458.74 sec	100	See Appendix	"IMG_9309.MOV"
Current & Broken Ice & Weathered Emulsified Crude Oil	0.8 ft/sec current, 20-30% broken ice coverage	21	43.37 sec	Was Not Achieved	267 sec	310 sec	35	See Appendix	"IMG_9349.MOV"

*Temperature is surface temperature unless otherwise noted. Average temperature during burn duration used. Temperature data recorded by CRREL.

Table 15: CRREL Test Result Averages – Baseline Control

	Time to Ignition (secs)	Time to Catch (secs)	Total Burn Length (Ignition to Finish) (secs)	Total System Run Length (secs)	Temperature* (°C)
Calculated Average from Table 13 and Appendix C.	54.05 sec	23.69 sec	196.34 sec	250.15 sec	373.33

*Temperature is surface temperature unless otherwise noted.

Table 16: CRREL Test Result Averages – SPORT PHII

	Time to Ignition (secs)	Time to Catch (secs)	Total Burn Length (Ignition to Finish) (secs)	Total System Run Length (secs)	Temperature* (°C)
Calculated Average from Table 14 and Appendix C.	37.71 sec	68.3 sec	289.6 sec	327.8 sec	350.25

*Temperature is surface temperature unless otherwise noted.

Table 17: Simplified CRREL Test Results - Baseline Control

	Total	Percentage of Total
Baseline Control Tests Performed at CRREL	9	
Successful Tests	3	33%
Failed Tests	6	67%

Table 18: Simplified CRREL Test Results - SPORT PHII

	Total	Percentage of Total
SPORT PHII Tests Performed at CRREL	23	
Successful Tests	9	39%
Failed Tests	14	61%

Table 19: CRREL Demonstration Verification Objectives

Objective	Pass	Fail	Observations
Demonstrate the basic capability of ignition of large amounts of crude oil, both weathered and emulsified.	X		SPORT PHII ignited both weathered and weathered emulsified crude oil in quiescent and varying environmental conditions.
Demonstrate the ability to burn crude oil in ice, wave, current, and wind conditions.	X		SPORT PHII was able to ignite in all environmental conditions except wind.

6.3.1 CRREL Demonstration Observations

When comparing the SPORT PHII performance to the control data, on average SPORT PHII ignites the spill in a shorter time frame and burns the crude oil for a longer duration. It should also be noted that of the nine control tests that were performed, only 33% successfully ignited the spill using the butane torch as shown in Table 17. Of those three tests, only one was considered to be “caught”. Based on these results, SPORT PHII is a more efficient and effective method of igniting the crude oil than a butane torch. However, no gelled fuel was introduced into the tank for the control tests. In real life applications, an agent such as gelled fuel would be introduced into the spill to aid in the clean-up.

During the demonstration tests at the CRREL facility, SPORT PHII met all verification criteria. HOOPS, a type of crude oil, was consistently ignited in both weathered and ~30% water content emulsified conditions using the SPORT PHII coaxial ignition system. The crude oil on the surface of the tank would consistently ignite at an average of 37 seconds after SPORT PHII was activated and after an average of another 68 seconds the surface was fully engulfed. The crude oil burned for an average of 4 minutes and 49.6 seconds and it was noted that once lit, the crude would consistently continue to burn even after SPORT PHII was powered down and/or submerged and was no longer supplying oxygen, gelled fuel, or MAPP gas to the spill. However, in some instances, SPORT PHII was not able to be powered down prior to submergence and was still supplying MAPP gas to the spill.

Due to the available test equipment and tank size, multiple environmental parameters were able to be tested at this location. SPORT PHII was able to light the crude oil on the surface of the tank at least once in all quiescent, ice, current, and wave conditions into which it was placed. Also, SPORT PHII was able to ignite crude oil in a few scenarios with combination conditions.

Per Table 18, 61% of the tests conducted at CRREL were considered failures. Further details about these tests can be seen in Appendix C. The fourteen failed tests can all be classified under one of the following categories:

- Bad exothermic rod (5 or 7)
- Defective check valve (1)
- Flooded/rebuilt electronics bottle (1)
- Improper timing in electronics bottle/MAPP pressure too high (3)
- Unit ignited as planned but unable to light surface of crude oil (2)
- Battery did not have enough power to initiate ignition (2)

Five of the failed tests noted no sparks prior to gelled fuel flow. This is standard behavior for a broco rod that has gone bad or is deemed a "dud", as was learned in initial system testing completed prior to full unit assembly. Further investigation into the working life of these exothermic cutting rods and the ability to sit on the shelf prior to deployment is needed and is listed in section 7 as future work.

One of the failed tests exhibited a defective check valve. Upon the activation of the unit, the check valve was blown out and therefore not enough Oxygen was kept at the tip of the exothermic rod to enable ignition. The check valve on each igniter was inspected prior to each of the remaining tests.

One of the failed tests involved a flooded electronic bottle due to a defective o-ring. With water inside the bottle, the boards were ruined, and the system was unable to give proper commands to the solenoid valves or the ignition sequence. All o-rings were inspected prior to assembly and use in each of the remaining tests.

Three of the failed tests were due to improper release timing in the electronic bottle and/or MAPP pressure being too high. In these tests, the exothermic rod would spark and begin to ignite but would be extinguished by the gelled fuel flow. To remedy this, the release timing coded into the bottle was adjusted so that the flow of MAPP and gelled fuel was delayed from the ignition command to give the exothermic rod additional time to ignite. When this did not consistently remedy the issue, the MAPP regulator was adjusted such that the pressure was less and it would propel the gelled fuel at a slower rate. Further testing and investigation into the appropriate MAPP pressure and means to ensure each mixed batch of gelled fuel has the same viscosity is needed and is listed in section 7 as future work.

In two of the failed tests, SPORT PHII functioned completely as designed but was unable to ignite the surface of the crude oil in the given environmental conditions. In one instance, the generated flames were pointed straight into the air instead of downward towards the surface of the spill. In the second instance, the flames pointed downward directly onto a block of ice instead of touching the surface of the oil. It is desired in the future to optimize the igniter design such that failure points can be controlled and the outputted flames will also point towards the surface of the spill. This is listed in section 7 as future work.

Two of the failed tests were left submerged overnight for a minimum of 12 hours prior to testing. Both failed to create any sparks when activated. These two failures may have been caused by either a bad exothermic rod, or the batteries having been drained enough that there was not sufficient power remaining to control all three solenoid valves as well as give the ignition command. Gelled fuel flowed in both instances, showing that there was some power remaining in the batteries. However, no sparks were observed, so either the ignition command was unable to be delivered or the broco rod was no longer active. Investigation into the shelf life of the exothermic rods and further testing of the batteries are listed in section 7 as future work.

Table 20 details the failure modes discussed previously in this section. Take note that the two failures attributed to battery power could also have been a bad exothermic rod. It is also noted that in two of the failures SPORT PHII functioned exactly as planned but simply failed to ignite the oil spill.

Table 20: CRREL Failed Test Results

Failure Mode	Quantity
Bad exothermic rod	5 or 7
Defective check valve	1
Flooded/rebuilt electronics bottle	1
Improper timing in electronics bottle/MAPP pressure too high	3
Unit ignited as planned but unable to light surface of crude oil	2
Battery did not have enough power to initiate ignition	2

A large takeaway from the CRREL demonstration tests was that additional research and testing is required to take the last steps to a fully commercially ready system. The additional testing required is detailed in section 7.

6.4 SPORT PHII Test Results

Table 21 details the overall performance of SPORT PHII at all three testing facilities. 50% of the time the system was successful in igniting the simulated oil spill in the conditions in which it was placed. Section 7 details the additional work that can be completed to increase the success percentage.

Table 21: SPORT PHII Test Result Performance

	Total	Percentage of Total
SPORT PHII Tests Performed	38	
Successful Tests	19	50%
Failed Tests	19	50%

6.5 Temperature Observations

In initial system testing at the Phoenix facility, the SPORT PHII generated flames reaching as high as 1800 F. This was determined using thermocouples placed near the tip of the exothermic rod and a few inches farther out in the center of the burn. This temperature data was confirmed at the CRREL facility where the flames reached 800 °C, or 1472 °F (Test #10). Temperatures on the surface, where the crude oil was burning, are the more important temperatures to note. Surface temperatures were often close to the temperature within the flames, but sometimes surface temperatures were lower. The average temperature on the surface during SPORT PHII burns was approximately 350°C, or 662°F, as recorded by the CRREL team. The flash point temperature of ANS crude oil is 29°C and the average automatic ignition temperature of most crude oil is 205°C. SPORT PHII consistently generated surface temperatures above both of these values, thus proving the ability to consistently generate temperatures high enough to ignite the crude oil.

6.6 Technology Readiness Level (TRL)

Technology Readiness Level (TRL) is a type of measurement system used to determine maturity of a particular technology evaluated against certain parameters. In Phase I, the SPORT system advanced from a proof of concept at TRL 2 to TRL 4 as a prototype tested in a lab environment. The goal for Phase II was to advance SPORT to TRL 6.

At the completion of Phase I, the SPORT system reached TRL 4. The stage gates to advance to TRL 5 are as follows:

- Prototype of the technology has been demonstrated in relevant environments.
- Accuracy and precision of results have been documented.

The stage gates to advance to TRL 6 are as follows:

- Full scale prototype of the technology has been demonstrated in relevant environments.
- Future regulatory approvals and industry standards are included in the test plan

In Phase II, full-scale prototype of the technology was tested and demonstrated in multiple relevant environments. SPORT PHII was tested with dodecane in various environmental conditions at the Phoenix facility, with crude oil at MFRI, and again with crude oil and various environmental conditions at US Army CRREL for ignition capabilities. Additionally, the system was beta tested prior to all off-site testing to ensure it was functional and to accumulate initial data. In addition to full-scale prototype demonstrations, all results from beta testing and full-scale testing were documented to detail the progress and performance of SPORT PHII, thus advancing the TRL level and getting the system several steps closer to commercially ready.

7.0 FUTURE WORK

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

- Study and test the exothermic rods in greater depth to determine shelf life and reliability. It is desired that the cutting rod assembly can be built and left on a shelf until SPORT PHII needs to be mobilized. One of the primary setbacks of previous in-situ burning is the lack of reliability after long term storage, so further research and testing must be conducted to overcome this challenge.
- Perform additional testing on the gelled fuel and MAPP flow. Test results show that the pressure needed on the MAPP propellant is dependent on the viscosity and temperature of the gelled fuel. It is desired that there will either be a uniform pressure for the MAPP in combination with release timing from the electronics bottle that will work for all ranges of gelled fuel, or a more concrete way to ensure the gelled fuel is uniform between all mixed batches. In the current system, the timing in the electronics bottle and the MAPP pressure have had to be adjusted in the field to ensure the gelled fuel flows at the proper time and speed so as not to prevent ignition of the exothermic cutting rod.
- Optimize igniter design to control failure areas. As the rod burns, pieces melt and flames escape. It is desired that the failure points be controlled to direct the flames consistently downward to the surface of the oil.
- Study and implement the optimization of the exothermic cutting rod ignition timing with respect to the liquid fuel dispensing and ignition.

- Continue to perform additional testing in environmental conditions, i.e., wave, wind, temperatures, ice coverage, current, in a larger scale tank including testing with crude oil of various types, emulsifications and weathering.
- Perform additional testing on system batteries to ensure sufficient power when left powered for prolonged periods of time prior to activation. It is desired that the batteries placed into the system could be left up to 24 hours and still be able to fun the system fully.
- Perform additional control testing where gelled fuel is incorporated into the spill to get data more accurate to real life scenarios for performance comparison.
- Continue to evaluate integration to an autonomous underwater vehicle (AUV) payload system and refine and demonstrate the deployment concept in a simulated control scenario.

8.0 CONCLUSION

Overall, the test results obtained from development and testing of the SPORT PHII igniter system are encouraging as a reliable and effective method for in-situ oil burns at sea. The SPORT PHII system was able to ignite HOOPS crude oil both weathered and emulsified in various environmental conditions including current, waves, and ice. Timely refurbishment of the systems was also demonstrated during the on-site tests by replacing expended components.

9.0 CITED REFERENCES

This report is a system design package and technical reports of the BSEE Oil Spill Igniter System. All referenced documents can be found appended to the end of this document.

[1] Field Operations Guide for In-Situ Burning of On-Water Oil Spills, American Petroleum Institute (API) Technical Report 1252, First Edition, July 2015.
[2] Igniters and Ignition Technology for *In-situ* Burning of Oil Fact Sheet, U.S. National Response Team (NRT) —Science and Technology Committee, October 1995.
[3] Weather Windows for Oil Spill Countermeasures, Merv Fingas, Environmental Technology Centre Environment Canada, 2004.
[4] Guidelines for the selection of in-situ burning equipment, Oil Spill Response Joint Industry Project, IPIECA/IOGP 2014.
[5] 10040487 SUB-ASSEMBLY, COAXIAL IGNITER, BSEE-OSI
[6] 10024726 ELECTRICAL TRIGGER STATION, BSEE OIL SPILL IGNITER
[7] 10040506 ASSEMBLY, OIL SPILL IGNITER, BSEE
[8] DOC10036057 CALCS – BSEE OIL SPILL IGNITER – AUV LAUNCH MODULE
[9] 10040532 ASSEMBLY, LAUNCH SYSTEM MOCKUP, REDUCED VERSION
[10] 10040531 ASSEMBLY, LAUNCH SYSTEM MOCKUP, BSEE-OSI
[11] 10040630 CONTROLLER ASSEMBLY, BSEE-OSI
[12] Oil Spill - Behavior, Response and Planning, Open-water Response Strategies: In-situ Burning, Walton, D.W., Program Coordinator, National Institute for Standards and Technologies, Personal Communication August 1997.
[13] DOC10036040 PHOENIX TEST PLAN BSEE OSI PHII
[14] DOC10035725 MFRI TEST PLAN BSEE OSI PHII
[15] DOC10036041 CRREL TEST PLAN BSEE OSI PHII

10.0 DOCUMENTATION REPORT

This report is a system design package and technical reports of the BSEE Oil Spill Igniter System. The system design package documents are in support of the REFERENCE documents listed above and can be found appended to the end of this document after the above referenced documents. The contents of the system design package are:

1) DOC10035732 TEST PLAN, VALVE, BSEE OSI
2) DOC 10035957 TEST REPORT – VALVE FLOW, BSEE OSI
3) DOC10036060 BLOCK DIAG – ROOT, BSEE OSI PH2
4) DOC10036061 WIRING DIA – TRIGGER CONTROL, BSEE OSI PH2
5) DOC10036063 WIRING DIAG – IGNITER BOTTLE, BSEE OSI PH2
6) DOC10036064 PCB – IGNITER MAIN BRD, BSEE OSI PH2
7) DOC10036065 PCB – IGNITER DAUGHTER BRD, BSEE OSI PH2
8) DOC10036066 CABLE DIAG – W1 O2, BSEE OSI PH2
9) DOC10036067 CABLE DIAG – W2 PROPANE, BSEE OSI PH2
10) DOC10036068 CABLE DIAG – W3 FUEL, BSEE OSI PH2
11) DOC10036069 CABLE DIAG – W4 IGNITER, BSEE OSI PH2
12) DOC10036070 CABLE DIAG – W5 ANTENNA, BSEE OSI PH2
13) DOC10036073 BLOCK DIAG – ROOT, AUV MOCKUP, BSEE OSI
14) DOC10036088 WIRING DIAG – CONTROLLER, AUV MOCKUP, BSEE OSI
15) DOC10036089 CABLE DIAG – LARGE AUV MOCKUP, BSEE OSI
16) DOC10036090 CABLE DIAG – SMALL AUV MOCKUP, BSEE OSI
17) 10040471 MODIFIED FITTING, COMPRESSION ADAPTER – ¼ OD TUBE X ¼ NPTF
18) 10040498 TRAY, CHASSIS, CONTROL BOTTLE – 1-1/2” X 12” X 3/32” THK
19) 10040503 FOAM PACK, FWD AND AFT SECTIONS
20) 10040504 FRAMING, FOAM BALLASR – FRAMES 1 THRU 6
21) 10040505 SUB-ASSEMBLY, HOUSING-FOAM/FRAME, BSEE-OSI
22) 10040508 IGNITER CONTROL MAIN PCB, BSEE – OSI – PHASE II
23) 10040509 BRACKET, SUPPORT, FUEL CYLINDER
24) 10040510 BRACKET, CLAM SUPPORT, FUEL CYLINDER
25) 10040512 IGNITER CONTROL DAUGHTER PCB – BSEE – OSI – PHASE II
26) 10040513 PLATE, LOCKING, ELECTROMAGNET – 2.95” X 1.95” X 0.125” LG
27) 10040514 ROD, STIFFENER W/ TAPPED ENDS - #10-24 UNC-2B, 0.50” OD
28) 10040515 TUBE, STIFFENER – 0.50” OD X 0.37” ID

29) 10040516 TUBING, COMP FITTING, O2 & MAP – 0.25” OD X 0.186” ID
30) 10040517 TUBING, COMP FITTING, FUEL – 0.375” OD X 0.311” ID X 2.50” LG
31) 10040518 BRACKET, BATTERY MOUNT, CONTROL BOTTLE – 1-3/8” X 1-1/2” X 3/32” THK
32) 10040527 ROD, STIFFENER W/ TAPPED ENDS - #10-24 & ¼-20 X 0.50” OD X 2.00” LG
33) 10040533 ASSEMBLY, CRADLE, MOCKUP, BSEE-OSI
34) 10040534 ASSEMBLY, DOOR, BSEE-OSI
35) 10040535 ASSEMBLY, DOOR LATCH BSEE-OSI
36) 10040536 ASSEMBLY, FOOT SUPPORT BSEE-OSI
37) 10040552 SUB-ASSEMBLY, ANTENNA W/ CABLE, POTTED BOX
38) 10040553 POTTING BOX W/ MTG FLANGES, STYLE B – 2.0” X 1.5” X 1.0”
39) 10040615 BUNGEE CORD ASSEMBLY BSEE-OSI
40) 10040620 SUB-ASSEMBLY, CONTROL BOTTLE, BSEE-OSI
41) 10040628 SUB-ASSEMBLY, PCB STACKUP, BSEE-OSI
42) 10040631 MODIFIED ENCLOSURE – CONTROLLER, BSEE-OSI
43) 10040644 REMOTE TRIGGER ASSEMBLY – BSEE-OSI
44) 10040645 MODIFIED ENCLOSURE – REMOTE TRIGGER, BSEE-OSI
45) 10040655 PCB – REMOTE TRIGGER, BSEE-OSI
46) 10040660 SUB-ASSEMBLY, O2 & PROPANE SHUT-OFF VALVES W/ CABLE, BSEE-OSI
47) 10040666 FOAM, FWD SECTION NOSE – 10 X 3.75 X 4” THK
48) 10041011 FOAM, FRAME 2 – 10” X 3” X ¾” THK
49) 10041023 SUB-ASSEMBLY, FUEL SOLENOID VALVE W/ CABLE, BSEE-OSI
50) 10041027 SUB-ASSEMBLY, SUBSEA CABLE W/ SLEEVE – 2-PIN FEMALE X 8” LG
51) 10041028 SUB-ASSEMBLY, SUBSEA CABLE W/ BLUE SLEEVE, (W3) FUEL – 2-PIN FEMALE X 15” LG
52) 10041029 SUB-ASSEMBLY, SUBSEA CABLE W/ SLEEVE, CONTROL BOTTLE

11.0 APPENDICES

APPENDIX A: PHOENIX TEST RESULTS

Test #	Burn Event	Evaluating Parameters	Unit #	Burn Times (sec)				
				Rod Consumption	Liquid Fuel Flowing	Dodecane Simulant Burn Off	Observations	Test Video (Filename)
1	Ice	~20-30% Frazil Ice Coverage 3mm Oil Thickness AUV Deployable	4	45 sec	37 sec	22 sec	Broco rod ignited, gelled fuel met ignited end a few seconds later. Dodecane caught 29 sec after Activation, unit was powered down 22 sec later when broco rod burn complete, fire extinguisher applied shortly thereafter.	"Unit 4 Ice Dodecane Burn.MOV"
2	Current	Water Lateral Velocity 0.75 - 1.0 knots 3mm Oil Thickness AUV Deployable	3	N/A	N/A	N/A	Unit surfaced from simplified AUV mockup, igniter tip was caught under burn blanket that was in place to protect tank that had billowed out with the current. Once remedied, system was activated, gelled fuel flowed but no sparks and no ignition. Standard dud igniter behavior.	"Unit 3 - AUV Release - No Ignition.MOV"
3	Current	Water Lateral Velocity 0.75 - 1.0 knots 3mm Oil Thickness AUV Deployable	3	N/A	N/A	N/A	Unit surfaced from simplified AUV mockup, igniter tip was caught under burn blanket that was in place to protect tank that had billowed out with the current. Once remedied, system was activated, gelled fuel flowed but no sparks and no ignition. Standard dud igniter behavior.	"Unit 3 - AUV Release - No Ignition 2.MOV"

4	Wind	Wind Speed ~16 knots 3mm Oil Thickness AUV Deployable	1	49 sec	74 sec	60 sec	Unit surfaced from simplified AUV mockup, broco rod ignited and gelled fuel met ignited end a few second later. Dodecane caught 20 sec after Activation, unit was powered down and fire extinguisher applied 1:20 after Activation. Note broco rod only burned partially down.	"Unit 1 Dodecane Wind Burn.MOV"
5	Curre nt	Water Lateral Velocity 0.75 - 1.0 knots 3mm Oil Thickness AUV Deployable	2	N/A	N/A	N/A	Delayed release from AUV mockup, unit caught several places on billowed out fire blanket within small tank. Once surfaced, system was activated, gelled fuel flowed but no sparks and no ignition. Standard dud igniter behavior.	"Current - No Ignition Stalled AUV Release.MO V"
6	Curre nt	Water Lateral Velocity 0.75 - 1.0 knots 3mm Oil Thickness AUV Deployable	2	N/A	N/A	N/A	System was activated, gelled fuel flowed but no sparks and no ignition. Standard dud igniter behavior.	"Current - No AUV No Ignition.MO V"
7	Curre nt	Water Lateral Velocity 0.75 - 1.0 knots 3mm Oil Thickness AUV Deployable	2	35 sec	35 sec	38 sec	Broco rod ignited and gelled fuel met ignited end a few seconds later. Dodecane caught 21 sec after Activation, unit was powered down 45 sec after Activation, fire extinguisher applied 14 seconds after powered down. Note broco rod only burned partially down.	"Unit 2 Current Dodecane Burn.MOV"

8	Wave	Wave Height ~10 inches 3mm Oil Thickness AUV Deployable	3	55 sec	47 sec	23 sec	Broco rod ignited and gelled fuel met ignited end a few seconds later. Dodecane caught 40 sec after Activation, slightly delayed as waves were keeping igniter tip on tank rim. Unit was powered down 58 sec after Activation and fire extinguisher applied 5 seconds after powered down.	"Unit 3 Wave Dodecane Burn.MOV"

APPENDIX B: MFRI TEST RESULTS

Test #	Oil Type	Burn Times (sec)				
		Rod Consumption	Liquid Fuel Flowing	Crude Oil Burn Off	Observations	Test Video (Filename)
1	Neat	22 sec	38 sec	33 sec	Unit surfaced from simplified AUV mockup, broco rod ignited, gelled fuel met ignited end a few seconds later. HOOPS caught 15 sec after Activation, unit was powered down 30 sec later when flames started to engulf the unit and fire extinguisher was applied a couple seconds later. It is noted that broco rod only burned partially.	"IMG_9236.MOV"
2	Neat	47 sec	37 sec	26 sec	Broco rod ignited, gelled fuel met ignited end a few seconds later. HOOPS caught 21 sec after Activation, unit was powered down and fire extinguisher applied 26 sec later when flames started to engulf the unit.	"IMG_9238.MOV"
3	Emulsified	46 sc	39 sec	23 sec	Broco rod ignited, gelled fuel met ignited end a few seconds later. HOOPS caught 27 sec after Activation, unit was powered down and fire extinguisher applied 23 sec later when flames started to engulf the unit.	"20210302_121802.mp4"
4	Emulsified	N/A	N/A	N/A	Gelled fuel flowed but broco rod did not ignite so the HOOPS did not ignite. No sparks prior to gelled fuel flow, deemed standard dud broco rod behavior.	"IMG_9241.MOV"
5	Emulsified	34 sec	27 sec	42 sec	Broco rod ignited, gelled fuel met ignited end a few seconds later. HOOPS caught 17 sec after Activation, unit was powered down and fire extinguisher applied 42 sec later when flames started to engulf the unit.	"20210302_144111.mp4"
6	Emulsified	25 sec	20 sec	11 sec	Broco rod ignited, gelled fuel met ignited end a few seconds later. HOOPS caught 21 sec after Activation, unit was powered down and fire extinguisher applied 11 sec later when it was deemed the surface had caught to preserve the test tank integrity.	"20210303_085233.mp4"

7	Emulsified	28 sec	22 sec	15 sec	Broco rod ignited, gelled fuel met ignited end a few seconds later. HOOPS caught 19 sec after Activation, unit was powered down and fire extinguisher applied 15 sec later when it was deemed the surface had caught to preserve the test tank integrity.	"20210303_092222.mp4"

APPENDIX C: CRREL TEST RESULTS

Test # & Date/ Time	Test Type/ Variable(s) (C/Q/Fr/Br/ Cu/Wi/Wa & W/E)	Unit # (1-4)	Air Temp (˚F)	Water Temp (˚F)	Time to Ignition (Controller Activation to Crude Ignition*¹) (sec)	Time to Catch (Crude Ignition to Catch*²) (sec)	Burn Length (Crude Ignition to Extinguished) (sec)	System Run Length (Controller Activation to Extinguished) (sec)	Temp* (°C)	Notes/Observations
3/22 Test #1 3:01 PM	Quiescent Control Weathered Emulsified	N/A			N/A	N/A	N/A	2 min 34.76 sec	22 (On Boom)	Propane torch was used for control test, small flames appeared at 1:45, it did not ignite.
3/22 Test #2 3:08 PM	Quiescent Weathered Emulsified	1			N/A	N/A	N/A	18.40 sec	25 (On Boom)	Unit started submerged via pulley system to simulate AUV release, called it no ignition. Loud pop at beginning and some flame, but broco rod did not ignite. Appeared that check valve was blown out, looked crooked upon inspection, deemed faulty check valve. Gelled fuel flowed fine.
3/22 Test #3 4:20 PM	Quiescent Weathered Emulsified	2			N/A	N/A	N/A	27.95 sec	19 (On Boom)	More crude was added to the surface to replace some that had been burned off. Did not ignite, no flames at all. Gelled fuel flowed but no sparked or ignition. This looked like typical dud igniter behavior.

3/22 Test #4 4:57 PM	Quiescent Weathered Emulsified	4			37.63 sec (Lap 1)	30.83 sec (Lap 2)	7 min 33.84 sec (Lap 3 = 7:03.01)	8 min 11.49 sec	600 (In Flames)	No submergence, unit was just placed onto surface of water containing crude. No more crude was added from residual from prior test. Unit ignited as planned. Unit was not turned off prior to submergence to protect foam from burning, so gelled fuel, propane, and O2 continued to be released from unit and could have aided the duration of the burn. Last few minutes were patches of flames vs full surface burn.
3/23 Test #5 8:30 AM	No Oil, System Test for Submergence	3			57.75 sec (Lap 1)	N/A No Crude	2 min 33.88 sec	3 min 31.64 sec	Not Recorded	No oil on surface, submerged unit system test to troubleshoot. Unit surfaced properly and ignited on command and burned, no crude oil involved other than remnants on the surface.
3/23 Test #6 9:50 AM	Broken Ice Control Weathered Emulsified	N/A			N/A	N/A	N/A	1 min 34.31 sec	7	Propane torch was used for control test, timer started when torch was first applied to the surface. NO IGNITION.
3/23 Test #7 9:54 AM	Broken Ice Weathered Emulsified	4			N/A	N/A	N/A	26.19 sec	7	This was the test with the bottle that got water in it and was rebuilt with new boards. Igniter was submerged, surfaced into ice but did not

										ignite. System would not shut off so all 3 tanks were emptied. NO IGNITION.
3/23 Test #8 11:10 AM	Broken Ice Weathered Emulsified (sort of)	1			24.20 sec (Lap 1)	41.69 sec (Lap 2)	1 min 11.77 sec (Lap 3 = 30.08s)	1 min 35.97 sec	37	Igniter was submerged, no more oil or ice were added to the surface, so there was less oil and ice than intended for the first test. Due to failed prior tests, propane was backed off to 2 turns instead of 2.5 turns. Gelled fuel did not flow as quickly, and only reached the end when the unit was turned off. Otherwise, broco rod ignited with only O2 and burned the crude from the surface. Note: thermocouples are placed 1 under the surface, 2/3 on the surface, and 4 in the flames.
3/23 Test #9 1:58 PM	Quiescent Control Weathered	N/A			29.93 sec (Lap 1)	23.69 sec (Lap 2)	1 min 42.50 sec (Lap 3 = 1:18.81s)	2 min 12.44 sec	500	Timer was started when the torch was first applied to surface of oil. It lit and burned off all the oil. Weathered ignited significantly easier and larger than weathered emulsified.
3/23 Test #10 2:25 PM	Quiescent Weathered	2			32.36 sec (Lap 1)	49.93 sec (Lap 2)	2 min 2.83 sec (Lap 3 = 1:12.90s)	2:35.20s	700	This is the first test with the new coding in the board that backs the propane/fuel off 4 seconds after the ignition command to ensure the gelled fuel

										doesn't snuff out the sparks even when the fuel is warm and flows faster. Propane dial back to 2.5 turns. Additional oil was added to the surface after the control burn. Unit was submerged during control. Unit ignited and burned off all the crude oil on the surface, gelled fuel flowed properly after the ignition.
3/23 Test #11 3:15 PM	Waves Control Weathered	N/A			1 min 8.33 sec (Lap 1)	Was Not Achieved	2 min 0.81 sec (Lap 2)	3 min 9 sec	20	Wave height ~10 cm, 1 sec period. There is some dampening from the boom so it is not 100% what is happening in the oiled area. Timer was started when the torch first touched to the surface. Waves were started first and then ignition was attempted. Took 2 tried to ignite. Waves cause the oil to separate into two puddles, one ignited but the other did not.
3/23 Test #12 3:55 PM	Waves Weathered	3			51.87 sec (Lap 1)	Was Not Achieved	6 min 46 sec (Lap 2)	7 min 38.74 sec	100	Wave height ~10 cm, 1 sec period. There is some dampening from the boom so it is not 100% what is happening in the oiled area. Igniter was submerged during the control, additional oil was added after burn off, waves were started and then igniter was

										raised to surface in the waves. Igniter was never pulled under after burn was started as the waves kept flames away from the foam. Spill was split into two, only half the spill ignited. Gelled fuel eventually ran out but burn was kept going by the O2 and propane supply.
3/24 Test #13 8:25 AM	Frazil Ice Weathered	1			32.46 sec	2 min 22.97 sec	3 min 48.97 sec (Lap 3 = 1:26)	4 min 22 sec	480	Unit was submerged and oil added, ice added last, unit came up and ignited right away.
3/24 Test #14 9:10 AM	Frazil Ice Control Weathered	N/A			1 min 3.9 sec	Was Not Achieve d	6 min 5.72 sec	7 min 9 sec	600	Oil added and then ice, propane torch used for control, timer started when torch first applied, only one cotner burned, had to light a second time.
3/24 Test #15 10:05 AM	Broken Ice Weathered	2			N/A	N/A	N/A	24 sec	40	Oil and ice added while unit submerged, some frazil pieces remaining. Gelled fuel shot out really far, igniter did not catch. No ignition. No sparks, looked like a dud igniter.
3/24 Test #16 10:30 AM	Broken Ice Weathered	3			32 sec	39.53 sec	5 min 25.53 sec	6 min	400	Some gelled fuel remaining from last failed burn, unit ignited, was not shut off before submergence so propane continued to surface

3/24 Test #17 11:40 AM	Current Control Weathered Emulsified	N/A			N/A	N/A	N/A	1 min 54 sec	28	Ice eater used to provide current, placed in with igniter submerged and then oil poured. Did not inite with the propane torch.
3/24 Test #18 11:50 AM	Current Weathered Emulsified	1			N/A	N/A	N/A	15.73 sec	27	No additional oil was added after failed control. Unit surfaced, gelled fuel flowed but broco rod did not ignite. Looked like standard dud broco rod behavior.
3/24 Test #19 12:20 PM	Current Weathered Emulsified	2			N/A	N/A	N/A	17.60 sec	26	No additional oil added, some gelled fuel remaining from last failed burn, flames started but were extinguished. Unit did not turn off so propane continued to flow after submergence. Deemed improper bottle timing and/or propane flow too high.
3/24 Test #20 3:10 PM	Current Weathered Emulsified	3			47.77 sec	1 min 44.85 Sec	7 min 20.85 sec	8 min 9 sec	450	Current speed approximately 0.8 ft/sec which is close to towing speed. After some dry tests, **switching to 1.75 turns for propane regulator from here on out**. Rod was almost extinguished but had a second burst, unit did not turn off so propane continued to flow but was a separate pocket from the oil,

										unit burned off most of the emulsified oil.
3/24 Test #21 4:00 PM	Current Broken Ice Weathered Emulsified	2			43.37 sec	Was Not Achieved	4 min 27 sec	5 min 10 sec	35	Unit submerged, oil added, ice added, current turned on and then unit surfaced. Entire broco rod burned this time sticking with 1.75 turns of propane valve, unit pulled under to protect from burning then resurfaced to attempt to light additional portions of the spill but was not successful.
3/24 Test #22 4:55 PM	Current Broken Ice Control Weathered Emulsified	N/A			N/A	N/A	N/A	1 min 23 sec	33	Timer started when torch first applied, did not ignite.
3/24 Test #23 5:00 PM	Current Broken Ice Weathered Emulsified	1			N/A	N/A	N/A	1 min 40 sec	35	UNIT DID IGNITE, some flames appeared on the crude but not enough to consider "caught". Broco rod burned all the way down and flames started to point upward instead of towards the crude on the surface. Unit was submerged as it started to burn itself up. Determined that 1.75 turns are best for the propane flow to push the gelled fuel.

3/25 Test #24 8:20 AM	Frazil Ice Waves Weathered Emulsified	2			N/A	N/A	N/A	22.12 sec	28	Unit 2 was submerged in the main tank at 6pm 3/24 and left overnight until test time = ~14 hour submergence. Gentler waves were used, 10 cm wave height and 2.5 sec period. Gelled fuel flowed when unit surfaced and was activated, but there were no sparks at all and the unit did not ignite. Deemed either dud igniter and/or overnight/cold batteries not enough to cause sparks.
3/25 Test #25 8:30 AM	Frazil Ice Waves Control Weathered Emulsified	N/A			N/A	N/A	N/A	2 min 58.57 sec	28	Gelled fuel that remained after the last failed ignition burned but the oil did not catch.
3/25 Test #26 8:47 AM	Frazil Ice Waves Weathered Emulsified	3			N/A	N/A	N/A	24.25 sec	25	Unit 3 was submerged in the firth at 6pm and left overnight until test time = ~14.5 hour submergence. Additional frazil ice was added prior to surfacing. All liquids and gases flowed but there was no spark and the broco rod did not ignite. Deemed either dud igniter and/or overnight/cold batteries not enough to cause sparks.

3/25 Test #27 8:52 AM	Frazil Ice Waves Weathered Emulsified	3 (ish)			28 sec	Was Not Achieve d	1 min 33 sec	2 min 1 sec	25	The end of the igniter was lit with a butane torch, it ignited the gelled which which ignited the broco rod. This burned down and ignited the crude on the surface. Speculation that the batteries left overnight may not have had the power to provide the proper power surge to ignite the rod with the O2.
3/25 Test #28 9:42 AM	Broken Ice Waves Control Weathered Emulsified	N/A			N/A	N/A	N/A	1 min 21.63 sec	25	Unit was submerged while this control test occurred. Same wave conditions as previous test. Propane torch was unable to ignite the oil.
3/25 Test #29 9:45 AM	Broken Ice Waves Weathered Emulsified	1			N/A	N/A	N/A	3 min 8.88 sec	26	Still using 1.75 turns for propane. UNIT DID IGNITE and rod burned all the way down, but the oil did not catch. There was a large block of the broken ice under where the igniter tip started to droop and spew flames downward. Kemal suggested an aluminum check valve or some attachment to catch some of the oil that starts spilling out.
3/25 Test #30 10:45 AM	Broken Ice Waves Weathered Emulsified	4 (Bottle 2)			N/A	N/A	N/A	18.07 sec	27	20 cm wave height, 2.5 sec period, some broken ice but not full coverage. There were no sparks and the broco rod did not

										ignite. It was reignited with the propane torch but the rod still did not burn, only the propane and the gelled fuel. Looked to be standard dud broco rod behavior.
					N/A	N/A	N/A	2 min 40.91 sec	27	
3/25 Test #31 1:25 PM	Quiescent Weathered Emulsified	3			N/A	N/A	N/A	29.12 sec	39	1.75 propane turns, newly mixed batch of gelled fuel. This unit also included a metal ro as a bracer for the PVC pipe not to droop as it burns. No new emulsified oil was added. The broco rod lit but was extinguished as the gelled fuel made it through. It was relit with the propane torch and burned all the way down. Deemed improper bottle timing and/or propane flow too high.
					1 min 30.65 sec	Was Not Achieved	3 min 34 sec	5 min 4.68 sec	39	
3/25 Test #32 2:05 PM	Quiescent Weathered Emulsified	1			N/A	N/A	N/A	2 min 9.14 sec	40	1.25 propane turns, new oil added, included metal bracer rod again. No sparks at all, gelled fuel did not flow that we could see. After unit was pulled back out it appears the gelled fuel was just reaching the starting end of the broco rod. Looked to be

										standard dud broco rod behavior.
					N/A	N/A	N/A	2 min 57.95 sec	45	
** Additional dry tests in the small tank were run but not timed. These tests were video recorded. One did not work at all and had an anomaly where the valves apparently all closed after a couple seconds. Second dry test worked perfectly.										
*[1]Crude is considered "ignited" once it remains lit for ~15 sec and when the flames start to spread *[2]Crude is considered "caught" when the flames have spread and the fire begins to fully engulf the slick										

*Temperature is surface temperature unless otherwise noted. Average temperature during burn duration used. Temperature data recorded by CRREL.