

System Development of a Low-Emission Spray Combustor for Emulsified Crude Oil: Final Report

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EXECUTIVE SUMMARY

This report documents the technology maturation of individual components and subsystems of the Naval Research Laboratory / Bureau of Safety and Environmental Enforcement (NRL / BSEE) burner system, their respective verification in realistic burn conditions, and technology demonstration exercises for government agencies, spill equipment manufacturers, spill response planners, and others.

Technology maturation efforts have been directed to a number of the burner's components, including the ignition system, atomizer operability, and burner shroud material. The ignition system was successfully transitioned from a more complicated liquid-fueled torch to a modified commercially available propane torch that is more reliable and much less expensive. The atomizer (burner exit) was tested with a range of particulate sizes and was able to expel them into the burning spray plume, which evaporated off the surrounding oil as they passed through. An analysis of corrosive-resistant materials with similar strength to AISI 300 stainless steel recommended that Inconel HX is an affordable alternative that will be able to endure the highly corrosive salts present emulsified crude oil spray combustion.

System-level technology maturation efforts were focused on emissions measurements, wave motion, and the influence of debris. Emissions measurements were performed by the U.S. Environmental Protection Agency (EPA) and they measured 99.8% burn efficiency with very low levels of unburned hydrocarbons and soot, demonstrating highly efficient combustion in comparison with in situ burning. The burner was mounted onto a U.S. Navy barge and placed into the wave pool at BSEE Ohmsett to determine if the spray would impinge against the burner shroud during rocking motion. It was found that the residence times of the high-velocity spray in the burner was much shorter than that of the burner shroud's rocking motion. As a result, there was no spray impingement against the burner walls. Debris studies revealed that debris and sediment particles in the oil impacted the hoses and fittings much worse than they impacted the atomizer and spray plume. The solid particles created clogs at locations where the flow area contracted or the flow changed directions.

Public burner system demonstrations provided feedback from government and industry on how the burner can be integrated into spill response plans and with standard oil spill equipment. Questions were fielded about the burner's operational details and discussions about how the burner could be manufactured and deployed were held.

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SYSTEM DEVELOPMENT OF A LOW-EMISSION SPRAY COMBUSTOR FOR EMULSIFIED CRUDE OIL: FINAL REPORT

INTRODUCTION

This report summarizes the progress of this program over the course of execution, with respect to the objectives of the program and to the scheduled milestones and details of the specific activities. During the course of the program, the BSEE-funded, NRL-developed emulsified crude oil burner was refined and tested while parallel efforts to transition the technology to industry were carried out.

A range of objectives drove the efforts of this program. The original objective of this program, as stated in the statement of work, was to transition the Technology Readiness Level of a low-emission, low-pressure atomization and combustor system for emulsified crude oil from 4 to 8 so that the system design can be transitioned to a manufacturer. This effort included the maturation of a number of subsystems and components of the entire burner system. An additional objective that developed over the course of the program was the adoption of this technology by the oil spill response community, which includes the federal state, and municipal government agencies that statutorily enforce oil spill response policy, oil spill response companies that carry out spill efforts, and manufacturers that supply oil spill response equipment. The adoption of this technology would drive the transition of the technical details (design, operation, etc.) to a company that would manufacture, market, and distribute it. This report will describe both the technology maturation efforts and the transition efforts.

SCOPE

The scope of this program can be divided into two areas: the technology maturation efforts and the transition efforts. Much of this program was influenced by a previous BSEE-funded effort (inter-agency agreement E14PG00060) to prototype a medium-scale low-emission burner. The planned scope of the efforts for this program is contained in the following sections.

Technology Maturation

There were a number of technology gaps in the burner system that needed to be filled at the beginning of this program. Some were component or subsystem gaps, while others were system-wide gaps.

Subsystem/Component engineering gaps included the ignition system, burner structure material, ignition limit dependency on fuel properties, heat flux to the peripheral structure, and wave motion effects on the operability.

A concern voiced at the 2017 International Oil Spill Conference (IOSC) listening session and by Norwegian Clean Seas Association for Operating Companies (NOFO) was for the operation of the plasma torch, which was part of the larger ignition design requirement and used in initial prototyping. To burn oil and emulsions, the ignition source needs to be able to supply a stream of hot gases at or above the ignition temperature for the spray plume. Past studies have used a propane torch [1] and two commercial plasma cutting torches [2]. Though the plasma torches were not modified for thermal durability, they performed adequately for the 25% scale burner. Unfortunately, the higher heat flux of the 50% scale burner melted critical plastic components of the plasma torches [2], making them inoperable and highlighting the need for a different ignition approach. During the last program, the plasma torches were re-designed and tested to endure higher temperatures and glow plug torches were designed and tested for an alternative ignition source. The current

program shifted away from plasma torches to attempt a diesel glow plug-based system and then settled on the more reliable propane torch system.

Burner structural durability is an ongoing concern with the burner. Designs were fabricated from AISI 302 stainless steel [2], which endures the high temperatures well, but not the high-temperature salt corrosion. Efforts were underway at NRL to select an alloy for use in salt water-cooled exhaust gas ducting and the information from that study has informed the material design decisions for this effort, but such a selection is not the primary focus of this program. Instead, the following sections provides design guidance. The scope of this program did not include long-term durability studies.

When the burner is transitioned to a manufacturer, the structural design will need to be adapted for the corrosion and temperature cycling it undergoes during operation by refining the geometry, assembly, and material while maintaining the operational characteristics. The salts in the emulsified crude oil combustion products corroded the 25% scale burner components, constructed of AISI 302. A more temperature and corrosion resistant material, such as Inconel 625 or HX, will last longer. Thermal stresses and frequent temperature cycling caused deformation on the bulkheads and stressed the associated welds. These two processes eventually caused the corrosion, deformation, and failure of some of the weld seams around the bulkhead of the 25% scale burner. Although no operation-limiting damage was found with the 50% scale burner, repeated cycling would likely result in the shrouds breaking (the atomizer, however, saw no damage). Therefore, the burner geometry and material may need to be adapted to the high thermal stress, corrosion, while balancing the need to be disassembled for storage.

Another design concern was the atomizer operability with high viscosity or high density fuels, such as intermediate fuel oil (IFO) and weathered/emulsified crude oil. Though the atomizer has operated with near freezing, medium weight crude during the concept demonstration program [3], that atomizer was much smaller. The design space needed to be explored or accommodated for heavier crude oils or other fuels.

The heat flux from the burner to the ground and the the temperature of aluminum plates were measured in order to design the thermal management of the burner mounting structure. The cooling time after a test was also measured to determine how long it takes for the burner to cool down between tests. Though this is not a design requirement, ignition testing needed to be done with a cold burner for conservative results.

Finally, it was necessary to determine how the burner spray was influenced by sea state or waves. Initially, an oscillating platform was designed to simulate wave motion for the burner. That effort was abandoned for a more practical system demonstration and verification at Ohmsett.

Technology Transition

Transitioning technology to government and industry practitioners requires a great deal of effort and skills that are beyond the expertise of the authors and executors of this program. Much of that work has been coordinated by Karen Stone (Program Manager, BSEE), Holly Ricks-Laskoski (Code 1004, NRL), and Micaela Whalen (Senior Technology Manager, Techlink).

BURNER OPERATIONAL SPECIFICATIONS

The scale of the burner have changed with the prototype iterations. This program used 50% scale, based on a proposed burner size (nominal 100%). The smaller scales are functional and, if future technology transfer efforts require a more modular approach, may be more useful than the larger variant. The flow rates for three burner sizes are shown in Table 1 and Table 2 for SI and imperial units, respectively.

There are three details about the size scales and flow rates that must be considered when integrating the burner specifications of the burner into a larger spill response system and plan. First, the sizes scale linearly while the flow rates scales geometrically to the power of two. Therefore, the flow rates quadruple when the size doubles. Furthermore, the sizes are not restricted to the 13, 26, or 51 mm nozzle sizes. The burner can be scaled accordingly to whatever nozzle size suits the manufacturer. Finally, the burner heat transfer scales geometrically as well. As the size doubles, the burning flame area quadruples, which assists in the evaporation and combustion of the spray plume, but also increases heat transfer to the surrounding structure. This is especially useful with emulsions; we have observed that as the burner size increased from the 25% scale to the 50% scale, emulsions more readily ignited and burned.

Table 1 - SI-unit flow conditions for the burner at different size scales. Concept development was performed at the 25% scale. Demonstrations and emissions testing was performed using the 50% scale burner. The 100% or full scale burner has not yet been built and tested.

Size Scale		25%	50%	100%
Dia_{Nozzle} (mm)		13	26	51
\dot{m}_{Air} (kg/s)	Ignition	0.010	0.039	0.15
	Full	0.036	0.14	0.55
Δp (kPa)	Ignition	20	20	20
	Full	150	150	150
\dot{V}_{Oil} (L/min)	Ignition	1.0	3.9	15
	Full	4.6	18.0	71
\dot{V}_{Oil} (m³/hr)	Ignition	0.060	0.24	0.92
	Full	0.28	1.1	4.2

Table 2 - Imperial-unit flow conditions for the burner at different size scales.

Scale		25%	50%	100%
Dia_{Nozzle} (in)		0.51	1.0	2.0
\dot{m}_{Air} (SCFM)	Ignition	16	64	252
	Full	59	351	908
Δp (psig)	Ignition	2.9	2.9	2.9
	Full	22	22	22
\dot{V}_{Oil} (gal/min)	Ignition	0.3	1.0	4.1
	Full	1.2	8.0	19
\dot{V}_{Oil} (bbl/hr)	Ignition	0.4	1.5	5.8
	Full	1.7	11	27
\dot{V}_{Oil} (bbl/day)	Full	42	274	641

The full flow rates in Table 1 and Table 2 depend on piloting for highly emulsified flows and the true maximum flow rates have not been fully explored. Piloting has a significant effect on both the ignition and the flow range for oil-water emulsions; as the pilot heat rate increases, the emulsion ignition and burn range increases. We have observed that mixtures with 50% emulsions ignited with sufficient piloting, but the resulting flames were not as hot nor as luminous as lower emulsion fractions.

The full flow rates are not the maximum flow rates at which the flame lifts off and extinguished. The listed full flow rates correspond to the air compressors that were available. It is possible to either increase the air flow or the fuel flow to lean or rich blow out conditions. Generally, the authors ran the air flow at maximum flow and then increased the liquid flow until just less than the rate at which visible soot formed in the exhaust gases, downstream of the burning plume. It is possible that both the air and liquid flow rates can be increased to rates higher than listed in Table 1 and Table 2, but the air flow capacity was limited by the air compressor system.

Specifications were also outlined in a graphical abstract titled “Low-Emission Crude Oil Burner: Oil Spill Cleanup in the Field” (Peterson, 2021) and a manual titled “Low-Emission Crude Oil Burner: Manual and Specifications,” both of which have been released to BSEE. The former is in Appendix I for reference, the latter is in Appendix II. A video and article were produced by NRL as well to aid in technology transition efforts (U.S. Naval Research Laboratory, 2022; Pasquini, 2020), and a brochure was created and released to BSEE as well.

TECHNOLOGY DEVELOPMENT

This section is divided into component and system level development. There were a number of component or subsystem and system development gaps that needed to be addressed at the beginning of this program. The remaining gaps for future technology transition will also be addressed in the Future Work section. The basic systems and subsystems of the burner system in its operational context is shown in Fig. 1.

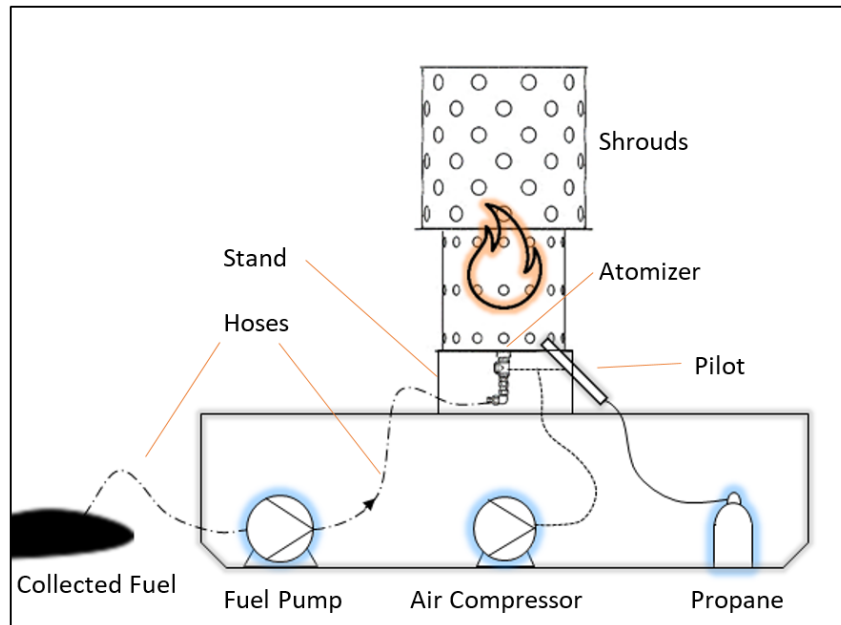


Fig. 1 - Diagram of systems of low-emission burner

Component/Subsystem Development

In this part of the report, the development of the most critical components and subassemblies for the operation of the burner are described. Each of them is required for the successful operation and transition of the burner to commercial production and widespread use.

Pilot

At the beginning of this program, plasma torches had been used for ignition. These were commercially available plasma torches (Miller XT series) that were used for cutting metals. When operational, they worked well, but they would only operate at 3 second intervals and when used with the 50% scale burner, the radiative heat transfer melted the plastic components. The original plan was to make plasma torches out of ceramic, but the prospect of using them in a marine environment suggested a number of serious operational and durability problems. Additionally the cost to manufacture became a dominant part of the whole burner system and needed to be reduced.

It was decided to use diesel engine glow plugs integrated into liquid-fueled torches. Though these were effective for small gas turbine ignition [4], as shown in Figure 2, they were problematic for this burner. They tended to clog, were not easily operated, and did not reliably ignite the burner.

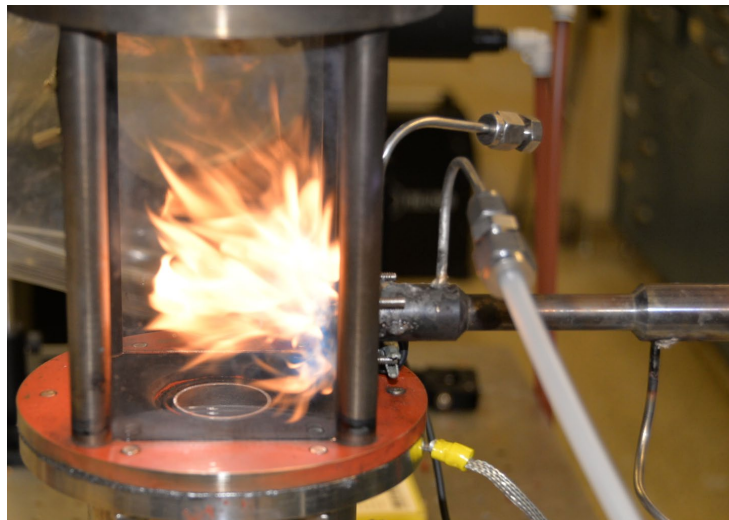


Fig. 2 - Glow torch with the NGK CZ 303 glow plug as it injects and ignites JP-5 fuel vapor into the cross flow of the optical combustion chamber.

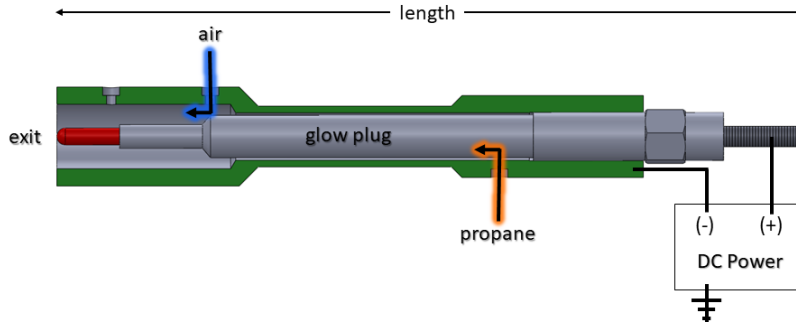


Fig. 3 - Intermediate design with propane and glow plug

After discussion with industry personnel, it was discovered that most vessels carry a supply of propane for cooking and heating. Therefore, propane torches were tested in the laboratory and it was observed that they ignited and burned more reliably and without the persistent liquid fuel leaking. The glow plug igniters were adapted temporarily to work with propane, as shown in Fig. 3. Then a commercial off-the-shelf Berzomatic torch, with some modification, was used for ignition, with one on either side of the atomizer. These have proven to be the most reliable ignition source.

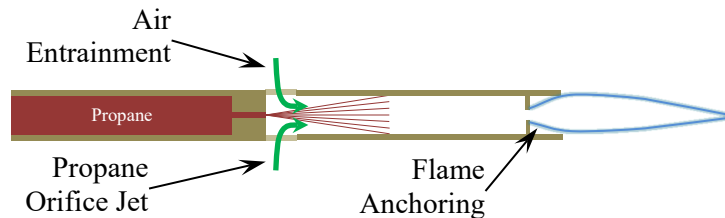


Fig. 4 - Simplified diagram of a conventional propane torch. The pressurized propane flows out of an orifice to form a jet that entrains ambient air. The mixture flows down a pipe and then combustion is anchored by a contraction and sudden expansion.

The torches in use now are conventional propane torches used for heating, brazing, and soldering metal (Berzomatic UL2317). Torch function and operation is shown in the diagram below in Figure 4. In order to protect the air inlet and fuel injection from the high velocity air and errant droplets at the base of the burner, along the bulkhead, tube section between air entrainment and the flame anchoring section was lengthened. This produced robust, stable flames that were able to ignite the spray plume rapidly and reliably. These torches have been able to ignite moderately weathered crudes up to 40% seawater. At greater emulsion fractions, the torches did not provide enough heat to fully ignite the spray plume. It is reasonable to suppose that greater heat release rates will more effectively ignite the spray plume as either the emulsion fraction increases or the oil's fraction of heavier weight constituents. This is assumed from observations of the plasma torches igniting emulsified crude oils; plasma torches provide much higher temperature gases so they were able to evaporate the water and oil and then ignite the oil. Larger propane torches will provide greater flow rates of high-temperature gases that will evaporate ignite the emulsified crude oil in a similar manner as the plasma torches.

There still remains some work to do with the torch ignition. As observed, they need to have a great heat rate to ignite fuels with longer evaporation and ignition delays, such as heavier, weathered, or emulsified crudes. This is discussed briefly in the Fuels & Emulsions section. A good pilot produces ignition in under a second, although it will always be condition- and fuel-dependent. They also require some fine tuning to optimize their design, durability, and operation; for instance they have valves to regulate the propane flow, and depending on the size of the burner this valve may need to be turned down (for a smaller burner scale) or possibly removed entirely.

Thermal Management

There are a number of thermal management issues that needed to be addressed. It was generally assumed that the burner would be stationed on a ship or barge deck, although the system could be operated on a drilling platform or land just as well, and discussions with different stakeholders illustrated that these were all feasible options. Main thermal issues include the metal temperature of the burner shroud, metal temperature of the deck, and heat flux to the deck. Measurements of shroud temperatures, simulated deck temperature, and deck heat flux were made to address thermal management design concerns.

Shroud Temperatures

Six thermocouples were placed on the burner shroud. One on the bottom bulkhead, two on the first stage and three more on the second stage, as labeled in Figure 5. The bulkheads refer to the horizontal sections where the cylindrical shrouds are attached to. The joint at the bulkheads was important to monitor to ensure no failure at that interface.

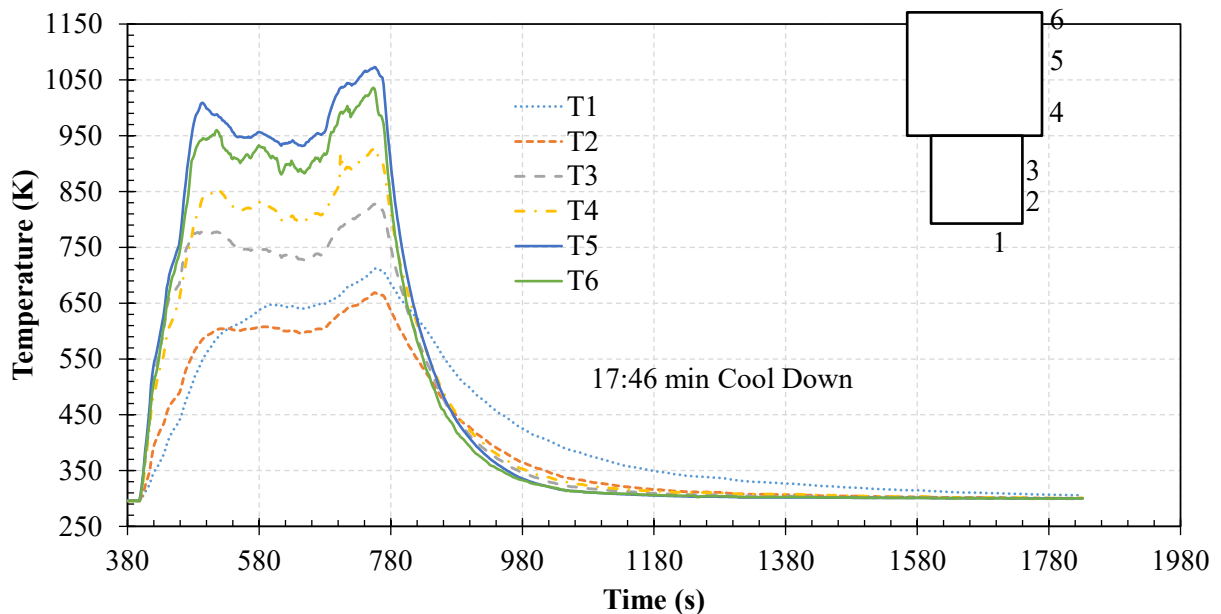


Fig. 5 - Shroud temperatures during a test with a specified flow rate of 40 L/min and air flow rate of 2.1×10^{-2} kg/s.

In general, the metal temperature increased along the spray plume, except for the bulkhead temperature, which was slightly hotter than the adjacent, bottom shroud temperature. The peak temperature was slightly

above 1430 °F (1050 K) at the exit lip of the burner. AISI 304 stainless steel is rated to 1500 °F, so this test approached the temperature limit for rated corrosion resistance.

It is possible to operate the burner with more or less shrouds. Initial trials found that two shrouds gave the best heat feedback while still allowing sufficient air entrainment to burn the flame cleanly, and kept the weight down compared to adding a third. One shroud alone meant that less of the flame’s heat was re-radiated back to the flame, meaning the burn was less clean. Two shrouds also provided more protection from wind and spray, although there is no evidence to believe that either would significantly alter the flame behavior.

Deck Temperature

Deck temperature measurements were simulated by placing 6 in × 6 in × 0.5 in 5000-series aluminum plates in a line extending out from the center of the burner at 4 ft increments (4, 8, 12, ..., 28 ft). Each block was drilled with a 3/16 mm hole and a K-type thermocouple junction was potted into the hole with thermally conductive epoxy. The blocks were painted flat black on one side and left shiny on the other to vary the emissivity. A temperature profile from a test is shown in Figure 6.

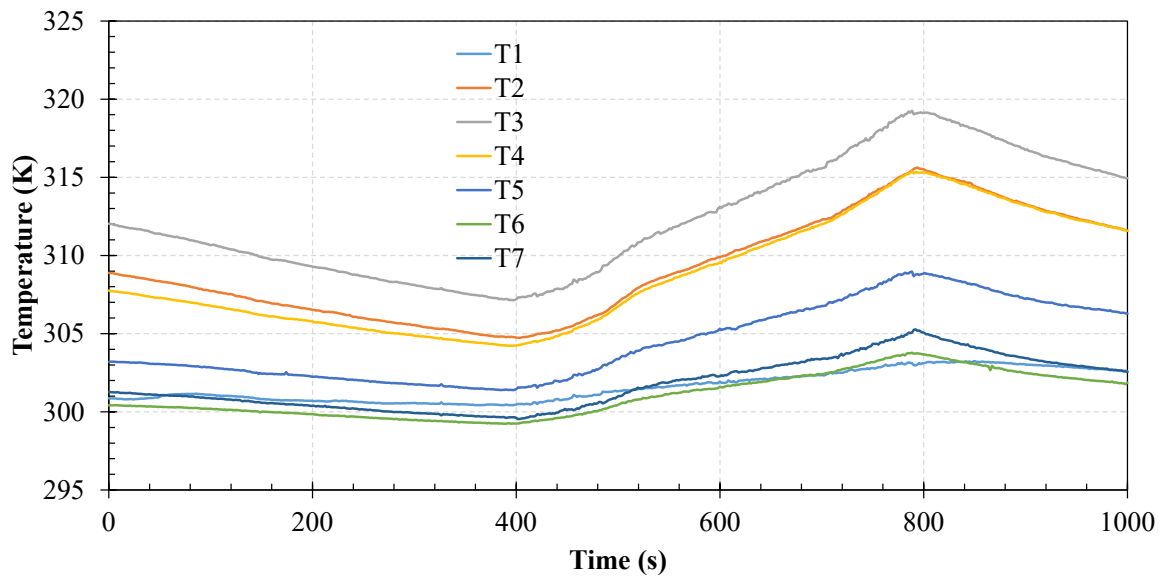


Fig. 6 - Simulated deck temperature measurements on the shiny, low emissivity side of the plates. Distance from burner in four ft increments starting from T1.

Here is a time trace of simulated deck temperatures over time as the fuel flow is increased and decreased. If profiles are compared, the peak temperatures were at 12 ft from the center of the burner. At this distance, the combined view from the burner flame and the hot burner shroud were sufficient to drive significant radiative heat transfer, but not to melting or damaging temperatures. The peak temperatures are less than boiling (373 K), but the structure of a deck has not likely been designed to withstand such high temperature over the entire area, which will cause thermal expansion, strain, and possible warping. Therefore, it is recommend that the burner be operated over water, water-cooled deck, or some sacrificial platform be used beneath it.

Deck Heat Transfer

Deck heat transfer profile measurements were performed during the BSEE/EPA/NRL emissions testing campaign. A heat flux gauge was placed on a skid in and moved in four-foot increments, radially, away from the burner. Table 3 shows a general trend of decreasing heat transfer, but this does not correspond with the peak temperature measured at T3 (12 ft) shown in Figure 6. Some of the data are missing that need some explanation. The 20191212 sets gathered on 12 December 2019 had difficulty with the measurement at 4 ft because the wires needed to be repaired and shortened. In other cases, data were not gathered due to safety reasons during testing.

Table 3 - Average heat flux data for the various oils and conditions tested during the BSEE/EPA/NRL emissions testing campaign.

Data Set File Name	V (L/min)	Heat Flux Profile (kW/m ²) at radius (ft)							
		4	8	12	16	20	24	28	32
201912121719_SampleMidWtNeat	9.9		0.87						
201912121604_SampleMidWtNeat	10.6		0.73	0.34	0.15	0.07	0.03	0.01	
201912121539_SampleHoopsNeat	12.5		1.38	0.76	0.41	0.24	0.16		
201912121527_FlowHoopsNeat	9.1		0.23						
201912121409_SampleMidWtNeat	13.4	1.98	1.06	0.62	0.35	0.18	0.11	0.07	0.05
201912121346_SampleMidWtNeat	11.9		0.64	0.31	0.20	0.14	0.10	0.07	
201912111421_SampleHoopsNeat	12.4	0.65	0.35	0.16	0.08	0.14			
201912111314_SampleHoopsNeat	12.4	0.73	0.41	0.18	0.08	0.03	0.01		
201912111243_SampleHoopsNeat	12.4	0.83	0.28		0.10	0.05	0.03	0.02	

These fuels presented were fairly volatile and expected to produce high-heat, highly efficient flames. These data are likely a conservative case, and the heat transfer is not expected to be higher than this in other cases. There may be an effect of fuel type on the heat transfer, but the effect is presumed to be small. A more dominant effect on the heat transfer is the scale of the burner, where a larger burner will have a larger total and per-area heat transfer.

Auxiliary Equipment

Long-term durability tests of the auxiliary equipment (fittings, hoses, pumps, air lines, control station, etc) were not done systematically, but since most of the equipment was used for hours of testing, some observations can be made. Some plastic covers on the data acquisition system within a fifteen feet radius showed some signs of light melting degradation after several tests, which is to be expected since they were not rated for high, or even moderate, temperatures. The liquid and air lines (made of Buna-N) also showed some slight degradation after multiple days of testing, and one started to develop cracks near a fitting (where the stress of a hose clamp exacerbated the issue) after weeks of testing. These hoses were also stored outside in the weather. Fittings and pump showed no signs of degradation. It is recommended that the hoses be stored carefully and inspected often, with the intention of replacing them if they are damaged.

Atomizer Operability

There were three atomizer operability issues that needed to be addressed: higher viscosity fluids, larger atomizer size, and the influence of debris. All of these are practical concerns voiced by outside reviewers and potential users. Though atomization, in general, produces larger droplets with increasing atomizer sizes and high viscosities, literature and our observations have shown otherwise. The flow blurring atomizer has been well demonstrated by a number of researchers [1,5-9] to produce fine, combustible sprays for highly viscous fluids. The presence of water and multi-component fuels tends to create a secondary atomization process [10]: as the droplet is heated, low-temperature boiling from water or lighter hydrocarbons burst the droplets into finer droplets, which more readily evaporate and burn. In our observations, even mid-weight crude oils burned cleanly and produced minimal soot, suggesting a very complete evaporation process.

Though debris had a negligible influence on the spray combustion process, it cannot be neglected when designing the support infrastructure for this atomizer and burner. Debris testing will be described in greater detail in the Debris section, but it is sufficient to note that debris did not have a noticeable influence on the spray combustion process other than that much of the debris did not have sufficient residence time in the flame to burn completely and ended up falling on the ground. Any oil that surrounded the pieces of debris was largely evaporated, but the debris that did fall did not have sufficient time in the burning plume to ignite or burn. Therefore, the debris and incompletely burnt that fell back to the ground did not create a fire hazard, but it is possible that they might present a potential pollution hazard because of the oil that surrounds them.

Burner Component Geometry and Material

There are two main subassemblies of the burner. The first is the atomizer while the larger and remaining structure is that of the burner shroud. The atomizer assembly is based on the flow-blurring atomizer [1,5-10], but has been modified to increase the turbulent mixing with the surrounding air. The modified atomizer design is currently in the process of being patented before the design is shared. For the atomizer assembly, AISI 303, 304, and 316 offered sufficient corrosion and temperature resistance since it did not experience sufficiently high temperatures to compromise its integrity. In contrast, the burner shroud endured much higher temperatures and salt corrosion [11-13]. To determine which metal should be used, temperature measurements were needed and the corrosion branch at NRL was consulted. They recommended that nickel-based alloys will provide the best corrosion protection, but those are the most expensive. Therefore, it appears that there is a balance between the cost of more frequent replacement of 300-series stainless steel second stage or a high-performance alloy version of the same part. A comparison of price and engineering properties in Table 4 reveals that weldable AISI 304 stainless steel and nickel alloys would be similar price. A reasonable alternative would be Inconel HX, which has comparable yield strength and price with a wider service temperature range.

Table 4 - Price comparison at an online materials vendor for various temperature and corrosion resistant materials for a 0.125" × 12" × 24".

Material	Price (\$)	Yield Strength (MPa)	Max Service Temp. in Air (°C)
AISI 304 Stainless Steel	502.62	275	925
Inconel/Haynes 625	519.59	414	982
Inconel 718	519.93	483	954
Inconel HX	502.82	372	1093

The fabrication of the burner shroud is also important. The initial, 25% scale prototypes used in the concept development phase experienced significant weld separation at the shroud-flange joint. This was due to thermal cycling strain and corrosion from the salts in emulsified crude oil sprays. AISI 304 also typically has problems with welds cracking from incompletely welded seams or thermal strain around the heat affected zone. These original welds were based on the welder's consultation, and were not placed with high cyclic stress in mind. A continuous fillet was welded at the flange face and ground smooth. This tended to crack and separated with repeated heating. Another weld was placed at the perpendicular joint on the other side, composed of 1/8-in tacks around the perimeter, spaced approximately 2" apart. These isolated welds also tended to crack and separate.

For the 50% scale burner, a continuous weld bead at the flange face was specified, again ground smooth. For the joint weld, 1/8" fillet welds, 1/4" long, spaced 1/4" apart were specified. These welds have not failed during the testing of the 50% scale burner. The short tacks, with the inherent thermal strain and rapid heating and cooling from welding, were problematic, while the longer heating and cooling times of the longer welds do not have the same cracking problems.

System Development

The system development and validation aspect of this program was concerned with how the burner would perform as part of a larger oil spill response system, which would include pumps, compressor, supporting infrastructure, and resulting performance. System level performance, in this case, includes the spill material throughput performance, pollutant emissions, operability with wave motion, operability with debris, and public demonstrations for technology transition.

Emissions

Emissions testing was performed at NRL's Chesapeake Bay Detachment (NRL-CBD) on 11-12 December 2019 in collaboration with the U.S. EPA and their collaborators. Dr. Johanna Aurell of the University of Dayton Research Institute, Dr. Brian Gullett of the EPA, and their team have generated a report describing their results and another paper describing their methods, so we will refer the reader to those documents [14,15]. It is worth noting some of the more

significant findings. First, the burn efficiency was very high – around 99.8-99.9% for almost all of the tests. That means that there was very little carbon monoxide (CO) or unburned hydrocarbons (UHC) in the exhaust. Soot emissions were also very low. Compared to in situ burning, the pollutant emissions were much lower. One curious note was a significant portion of methylene chloride detected and the source has not been determined. It appears it might be traced to cleaning agents used in the petroleum supply chain of the oils that were used.

The very low pollutant emissions and high burn efficiency can be attributed to a number of processes the atomizer, oil, and burner shroud produce together. The high turbulent mixing rates in the spray plume and the fine spray are produced by the atomizer. The jet exits at more than 100 m/s, as measured in laboratory studies [2], creating very rapid and complete mixing with the surrounding air. This produces a cleaner flame than simply spraying the fuel into the air by itself.

Crude oil, because of its asphaltenic and aromatic constituents, initially produces a highly radiant, sooty flame that then radiatively heats the non-transparent oil droplets, further accelerating the evaporation and burning process. Finally, the burner shroud does several things. It creates a flame-anchoring recirculation zone at the base of the burning spray plume while it shields the rest of the plume from surrounding winds.

Simultaneously, the shroud is heated by the radiant, sooty flames, which then heat the air that is entrained and mixed with the plume. This warms the air and the droplets, allowing them to vaporize quickly. As a result, the spray plume burns very efficiently.

Mounting & Wave Motion

During the week of 2 March 2020, operability testing of the burner with it mounted on a standard U.S. Navy Supervisor of Salvage (SUPSALV) barge was conducted with cold spray. This was to observe how the spray plume behaved while the entire burner structure was moved by the waves. Among the concerns before the test was whether the plume would impinge with the side of shroud in rough sea conditions. Should this occur, the impinged oil could create a fire as it falls down the burner structure onto the deck of a vessel. There was concern that it could also change the spray behavior in such a way that reduced the performance. As happens during systems tests in dynamic environments that are encountered during system deployment, this testing revealed conditions that can produce otherwise unforeseen behavior.

Since this test demonstrated the most mature system setup of the burner that has yet been attempted and gives the context for how the burner might be deployed, that test series will be described below in detail. Given the nature of the test site and permitting requirements, it was not possible to do hot tests. However, the flame behavior is dependent on the liquid and air flow behavior, which was detectable and would demonstrate if a failure mode might occur.

This test campaign evaluated the burner with cold spray on a realistic barge with waves of different heights and profiles and verified that the plumbing system operated as anticipated, the spray plume does not impinge against the wall, and uncovered some issues with field operability that had to be addressed.

Experimental Setup and Wave Action

The experiment was composed of three major systems working in concert. These include the wave tank, the barge and burner, and the flow control system.

The Ohmsett wave tank is an open-air saltwater tank 203-m long, 19.8-m wide, and 2.4-m deep (see Figure 7), operated by BSEE and contracted Applied Research Associates personnel. On one end is a wave generator that creates waves of various frequencies and heights. For sinusoidal waves, a wave attenuation system at the other end is raised from the tank floor that provides a near-anechoic boundary so that a near-sinusoidal wave state can be achieved for about 90 s. After that time, the mild wave reflections start to interfere with the sinusoidal wave geometry and the experiment is shut down. The tank then settles for 2-7 minutes, depending on the wind, which can drive additional waves from the existing peaks. For harbor chop waves, which are more dynamic, unsteady, and violent, the wave attenuator is lowered back to the pool floor and a hard wall boundary reflects the waves back along the length of the tank toward the wave generator system; this produces reflected waves that are incoherent and out of phase from the side-wall damping. The constructive and destructive interference creates a spatially and temporally non-uniform wave state that can produce higher wave peaks and more rapid pitching motion that the sinusoidal, damped arrangement can generate.

Future use of the burner at sea or near the coast may involve different types of waves, and NAVSEA SUSALV crew and Ohmsett were consulted on site as to what the likely limits of wave height and frequency were for the barge assembly. SUPSALV will field their equipment when it is safe to do so, and so there are limits to when the barge (and therefore burner) might be operable. This is also true for mechanical collection, in situ burning, and any other recovery efforts during a spill.

The barge and burner assembly, shown in Figure 8, was the second major system of this experiment. The burner has been described in previous work [2]. The barge, specified as the P06400 Modular Working Platform, is part of the standardized SUPSALV equipment listed under the Emergency Ship Salvage Material (ESSM) inventory. In general use, the full barge is composed of four sections; two wide and two long. Each section is 8 ft wide, 24 ft long. Thus, a full barge is 48 ft long and 16 ft wide. For this test, the plan was to expose the burner to as much motion as possible while minimizing the equipment requirement, so only a half-length, full-width section was used, making the test barge 24 ft long and 16 ft wide. A longer barge would experience less rocking motion.

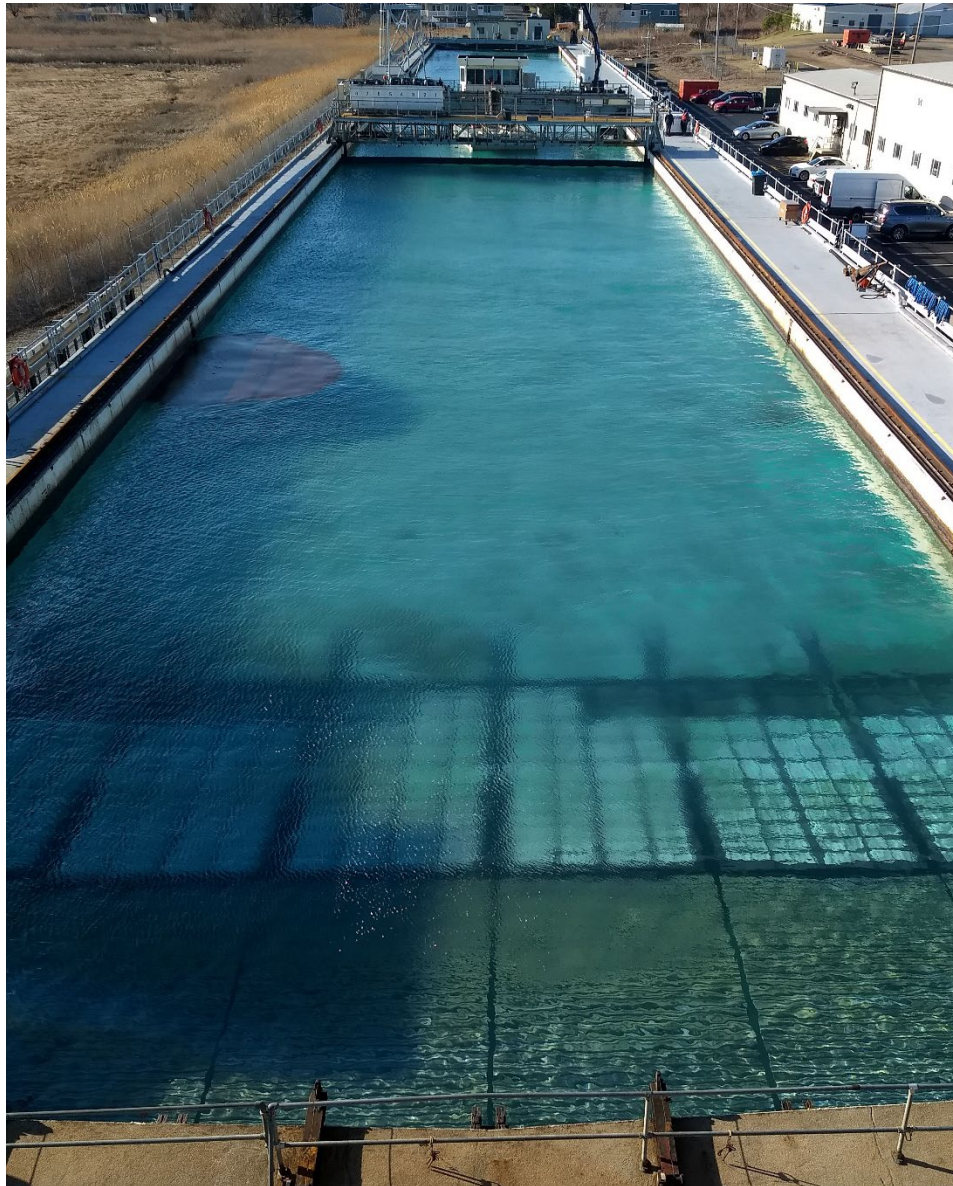


Fig. 7 - Photograph of the 203 m wave pool. The submerged wave attenuator, or “beach” is in the near end of the pool and the wave generator is in the far end. Two bridges (or gantries) surround the test area where the barge was located. The nearest is the containment bridge and the furthest is the control bridge.

The air flow and control subsystem was composed of a 375-CFM air compressor, 2-in-diameter hoses connected by 4-lug claw fittings (Dixon Air King), valves, and a laminar flow element to measure air temperature, pressure, and mass flow in CFM. The water flow subsystem was composed of a diesel-powered hydraulic power unit, connected via hydraulic hoses to a pump submerged in the tank. This equipment, excepting the laminar flow element, was provided by SUPSALV and was all equipment used in actual spill and recovery scenarios.

For each wave state, the flow was initiated at 1-3 GPM of water and 56-60 CFM of air. The liquid flow was then turned up to 4 GPM as the air flow was increased to around 140 CFM. The liquid was then increased to 7 GPM and the air was increased to 200 CFM. Finally, the liquid flow was increased to 10 GPM and the air was increased to 345-350 CFM.

Because the shrouds have large holes for air entrainment, impingement would be possible to observe as water would exit these holes. Video was recorded for later analysis if this was the case.

The burner was setup so as to be connected to pumps and air lines that extended off the barge. No personnel or auxilliary equipment was on the barge during operation with the burner assembly. Other use cases (including use of the full-size, four-piece platform), could involve placing equipment nearer to the burner, although this is not recommended without further testing and a hazard assessment.

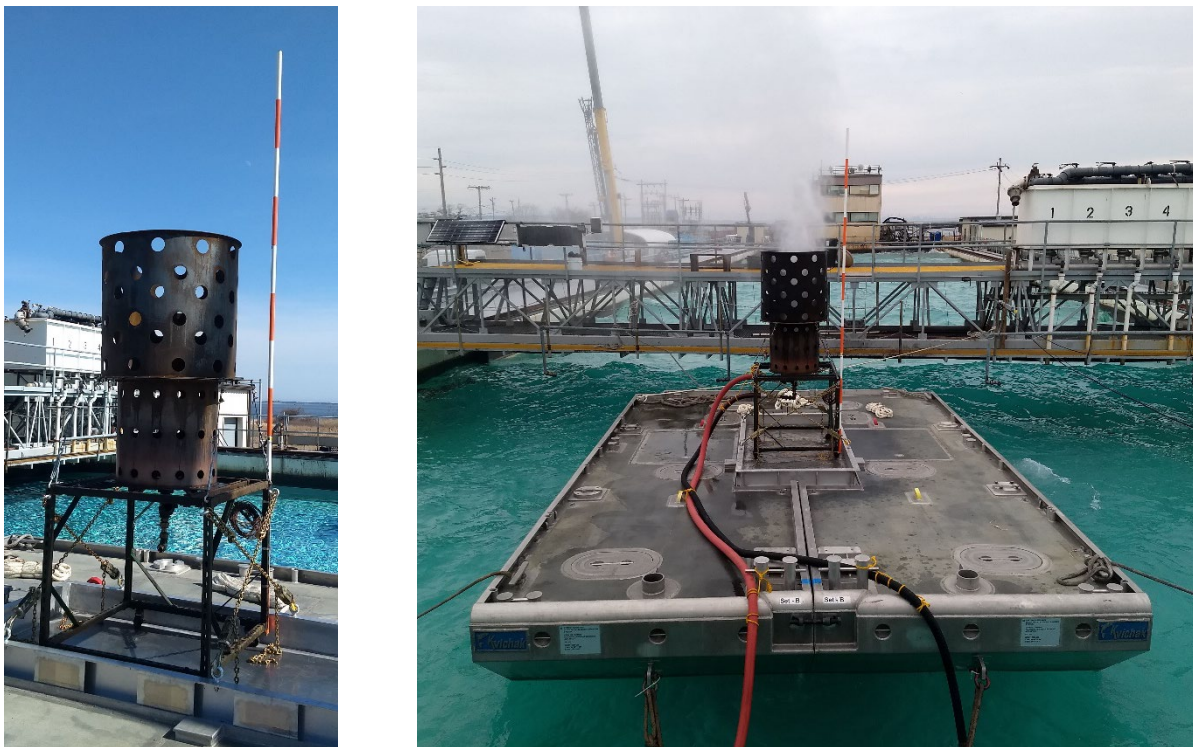


Fig. 8 - (L) Photograph of the burner, burner frame, vertical reference survey pole, and mounting arrangement of the barge. (R) Front view of the two-wide modular barge assembled with the burner, hoses, and vertical survey pole for angular reference during a spray test. This barge had a 24-ft length and 16-ft beam. It was secured at the bow by two lines to the control bridge visible in the lower left and right of the bow, close to the hoses. Two additional lines were secured to the stern and crossed to mount to the containment bridge.

Results

Tests were conducted over two days. The first day, 2 March 2020, was primarily focused on installing and assembling the equipment. The installation of the on the barge was rather simple: eyebolts were mounted to the burner's channel-strut frame and the whole assembly was lifted with a crane. Four steel cables with turnbuckles secured the assembly – the steel cables are preferable to synthetic straps due to temperature issues. A set of initial tests were done, as shown in Table 5, to observe if the barge sections' connections and that the burner mounting could endure the rocking motion without any sort of structural failure. The tests indicated no problem, so the next full day of testing with both spray and waves was planned.

The following day, 3 March 2020, the tests, as outlined in Table 5, were conducted. For each spray test, the flow was initiated and increased as described above. It was observed that until 200 CFM, the rocking motion of the barge produced oscillations in the liquid flow rate. It was thought that this was caused by oscillations in the back pressure head as the hose was raised and lowered with the rocking barge. To overcome the oscillating liquid flow rate, a valve restriction was installed in the liquid flow line, just upstream of the atomizer. This added a considerable pressure bias to the upstream liquid flow that was appreciably higher than the oscillations in the liquid pressure head from the rocking barge and attenuated the flow oscillations, such that they were not noticeable for subsequent tests.

No water was seen exiting the shroud through the sides at operating conditions, which demonstrated that the jet was not hitting the walls but was instead exiting the top at high velocity, as designed.

Table 5 - Experimental conditions for the wave tank. \bar{H} designates the wave height, which was constant during the test.

Test #	Date	Freq. (CPM)	Stroke (in)	Wave	\bar{H} (in)	Notes
1	2020 March 2	11	22	sine	8.44	No spray. No problems.
2	2020 March 2	12	22	sine	9.32	No spray. No problems.
3	2020 March 2	18	18	sine	15.02	No spray. No problems.
4	2020 March 3	25	7.5	sine	8.97	No spray. No problems.
5	2020 March 3	25	15	sine	20.66	Spray, but did not cause spray impingement.
6	2020 March 3	20	15	sine	14.95	Explored, but no full spray
7	2020 March 3	25	12	sine	n.d.	Explored, but no full spray
8	2020 March 3	25	15	sine	20.66	This broke the control system; paused for system restart
9	2020 March 3	30	12	sine	18.82	Incomplete test; waves too violent
10	2020 March 3	30	6	sine	n.d.	Spray, but did not cause spray impingement.
11	2020 March 3	30	8	sine	11.03	Spray, but did not cause spray impingement.

12	2020 March 3	27	9	harbor	23.65	Spray, but did not cause spray impingement.
13	2020 March 3	27	9	harbor	23.65	Valve installed to attenuate oscillations. Spray, but did not cause spray impingement.

Wave Motion Conclusions

There were concerns that the spray plume would impinge against the shroud, in particular the high velocity core of the jet. Instead, the spray plume did not impinge in any way. The oscillations to the liquid flow rate had a much greater potential to cause ignition or flame behavior problems. With some creativity and ingenuity from the SUPSALV team, that problem was resolved and consistent, steady spray was observed even at the worst harbor chop conditions the Ohmsett team were able to generate. This issue and its solution is worth noting for any future use where the assembly (and hoses) experience a vertical motion.

The spray oscillation was resolved by placing a pressure drop, or flow restriction from a valve, just upstream from the atomizer. In actual deployment of this burner, it may be that the burner is not considered safe to operate in rough waters due to oil delivery and connections issues. If it is considered safe, the flow restriction needs to be a standard components of the liquid flow assembly.

A more pressing issue is how the rest of the equipment operates in different sea states. The power unit, pump, and hoses are all connected and have set lengths – too much motion can cause disconnections, etc. This was observed in one of the tests; the burner remained intact during trial 8, for instance, but the upstream system was limited by the rocking motion. This issue, while important, is not specific to this burner and is true in whatever context that equipment is used in.

Debris

One of the ongoing concerns that planners, manufacturers, and users have voiced is the influence of debris on the atomizer and subsequent combustion. There are three main subsystems that can be impacted by debris:

1. Pump – the oil pump systems used in oil spills are generally hydraulically-driven Archimedes pumps. These pumps tend to macerate debris well, but there are limits to size and quantity of particulates. The underlying question for the component operability downstream of the pump is whether the size distribution of the debris that exits the pump will create clogs.
2. Atomizer – the spray system is not mechanically actuated in any way; the geometry and flow conditions provide the atomization. If there are obstructions, it will be because the size or number density of the debris is too great for the diameter and flow geometry of the atomizer. The underlying issue is what the limiting size or number density of the atomizer.
3. Burner – though the turbulent burning plume is capable of cleanly burning crude oil, how debris particles behave in the burning plume has not been fully examined. This brings up significant questions. What is the limiting size or number density of the solids burning in the plume? What is the condition of the oil-covered particles that are not burned, but fall out of the plume?

NRL requested that SUPSALV test one of their commercial pumps and a skimmer with water and debris, such as might be used in the field. They sent NRL the processed debris. The mass distribution was measured as a function of size ranges, shown in Figure 9.

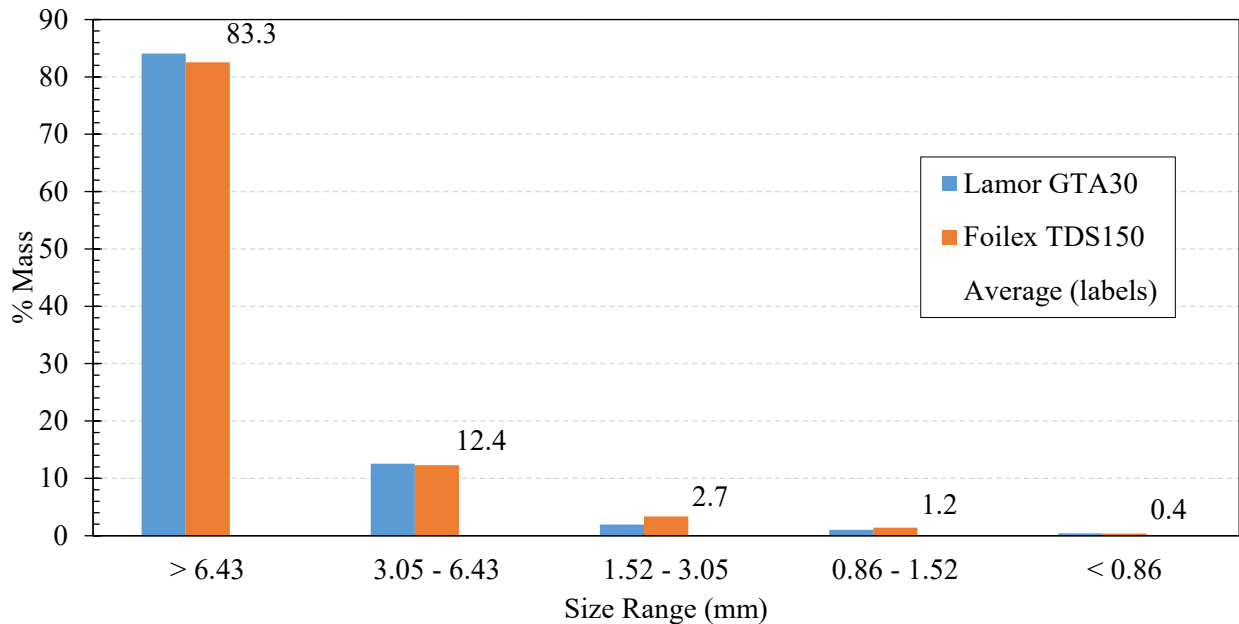


Fig. 9 - Percent mass distribution by size ranges (largest dimension) for the two pumps used by SUPSALV to macerate debris.

In order to replicate similar behavior, shredded hardwood mulch was used as a debris analogue with a similar size distribution and mixed in with crude oil. It was then pumped through a progressive cavity pump toward the burner. A number of issues were observed in the process.

If the debris was able to pass through to the atomizer, there were no clogs because of the open, smooth geometry of the atomizer channel. However, the pump, lines, and an elbow upstream of the burner repeatedly clogged. These clogs created severe backpressures that caused bursts in some hoses. It was also observed that many of the solids that were expelled from the atomizer were not burned. A coating of varnished tar appeared to coat the debris particles, but they did not appear to be charred. This suggests that the volatile fractions of the oil surrounding these pieces evaporated and even burned, but the debris itself did not persist in the burning plume long enough to ignite or burn. Finally, it was observed that the expelled pieces were thrown into the air and then were carried by the wind across a wide area of the test platform (on the order of fifty feet). This behavior may make it difficult to contain the spread of potential pollutants during a spill remediation effort.

Due to the clogging of the upstream hoses and junctions, the negligible debris burning, and the scattering of the tar coated debris, it is advisable that pieces of debris be filtered out of the gathered oil before it is pumped into the burner. Although there is not evidence of the debris reliably igniting, there is the possibility that different types of debris (besides the hardwood tested) may be more ignitable. Should solid particles be intentionally pumped through the burner, the risk that they are ignited and then scattered onto oil slick may create a potential fire hazard that should provide additional motivation to remove debris from the oil prior to burning.

Fuels & Emulsions

The low-emission burner system can be used for different types of fuels and can burn some fuels with water in emulsion. This may occur in a situation where a fuel spill is gathered directly from the sea surface and pumped into the burner, or where stored oil has water mixed in and is agitated enough to form an emulsion. Over the program's period of performance, crude oils were burned (HOOPS, Endicott, Santa Clara, Oriente, a mixed mid-weight blend, Carpinteria, Santa Ynez). A brief but unsuccessful attempt was also made to burn Hydrocal 300 since it was available, but this oil would not be a good candidate to burn with any ignition method.

Several of the crude oils were attempted with simulated seawater (ASTM D1141-98 salt solution added to water) emulsified with the oil. The range of how much water the oil will uptake is highly oil dependent, and the amount of agitation and temperature (such as wave and weather conditions) matter. The highest water content that successfully burned was 60% seawater, but the ignition took significantly longer. Since the test apparatus did not allow for us to determine the true stability of the emulsion or keep an unstable emulsion constantly mixed (a mixer was run inside of a tote and then removed for the testing in order to attach the hoses), it was found that the high-water content emulsions started to break down during the test run.

When the emulsions break down (as might happen if an emulsion in the field is collected in a tank or bladder and then allowed to decant), they create the increased possibility of water "plugs" in going to the burner. This occurs when a significant amount of water without any oil travels through to the burner and could cause some issues. This was tested and the liquid fuel / glow plug pilot system would sometimes go out, rendering it useless. The propane torch pilot, being higher velocity, positioned farther away from the atomizer exit, and hot enough, did not have this problem. However, the water did cool down the flow and caused the next section of the fuel/water mixture that did ignite to produce a dirtier, sootier flame. This is detailed further in the emissions report [14,15]. Forty percent water with the lighter crude oil (which had more volatiles) seemed to produce repeatable, reasonably clean results.

Weathering of the fuels will of course have an effect on the ignitability of the burn, in part because the volatiles evaporate as the fuels weather after a spill. In our tests with some weathered fuels, ignition appeared to be difficult (Carpinteria) or impossible (Santa Ynez). However, if the oil did ignite, it burned cleanly (water plugs not withstanding). A full catalog of fuels, emulsion percentage, and degree of weathering is not feasible for any operator to undertake, so a general recommendation is to prioritize burning light fuels with the minimum amount of weathering possible in the situation. For weathered and heavier fuels, it is recommended to allow some decanting to occur and have the water removed if possible. The operating range will also be affected by the weather conditions in the field.

Public Demonstration

There were a number of public demonstrations that were planned for this program in order to allow government agency spill remediation planners, petroleum suppliers, oil spill equipment suppliers, and others to witness the burner's performance.

An early plan was to conduct a demonstration at the former Joint Maritime Test Facility (JMTF) that was operated by the U.S. Coast Guard. For this demonstration, SUPSALV would supply the necessary diesel powered air compressor, diesel-driven hydraulic pump, hydraulically driven oil pump, air metering equipment, and the required hoses and fittings. This plan was cancelled when the U.S. Coast Guard decided to close and dismantle JMTF, permanently removing the opportunity to conduct a public technology

demonstration that would also provide a system level test of all of the necessary support infrastructure that would be required for the burner to operate.

Next, a demonstration was planned for the 2020 International Oil Spill Conference (IOSC) with site and infrastructure support from Clean Gulf Associates, an oil spill response company. The 2020 conference was postponed to 2021 and then made virtual, so that public demonstration was cancelled.

Finally, a public demonstration was planned and carried out on 30 March 2022. There were representatives from BSEE, NOAA¹, EPA, U.S. Coast Guard², ESSM, API³, SAG⁴, SCAA⁵, Elastec⁶, Lamor⁶, PCCI⁶, Exxon-Mobile⁷, Chevron⁷, MSRC⁸, and others that met at in Chesapeake Beach, MD. There were presentations of BSEE's technology objectives and application, and then the guests and BSEE personnel boarded a bus to NRL's Chesapeake Bay Detachment. Once there, Dr. Tuttle and Mr. Pfützner provided the spectators with a safety brief and ear plugs, started the diesel-powered air compressor, ignited the ignition torches, turned on the air flow to ignition flow rate, and then turned on the oil flow to ignition flow rate. A second or two after the spray formed, the burner ignited. Once the burner operated for about 5 minutes and the barrel of oil was drained, the burner was extinguished and the attendees and NRL staff discussed the burner operation, performance, and other design aspects. During discussion, a number of important concerns were raised by the participants that need to be addressed. Though many of these are not within the scope of the statement of work or would need to be resolved by the manufacturer, distributor, and end user, they are outlined below.

Burner Permits

The burner will need to be permitted by state and federal agencies to operate. Permitting is required to reassure the public that the burner will not only produce clean emissions, but will not produce a fire onboard the vessel, unburned oil overspray that might get carried away, leak unburned oil, or some other hazard. Though the permitting is a prerequisite to operating the burner, it will fall to the manufacturer, distributor, and user to negotiate these details while developing an oil spill response plan. As research engineers, this is not an area the authors are familiar with nor is it within the scope of the program.

Burner Heat Transfer

The heat transfer from the burner to the deck of the vessel poses a potential risk of structural damage by causing thermal strain and weakening that can then result in deformation and structural failure. There are a number of ways that the heat transfer damage risk can be mitigated, especially for aluminum decks, but the simplest may be to constantly pour or spray water over the deck. This approach cools the underlying metal and provides a fire retardant.

¹ National Oceanic and Atmospheric Administration, Department of Commerce, United States Government

² The U.S. Coast Guard administers and manages oil spill operations on all U.S. waters.

³ American Petroleum Institute – a non-profit petroleum production research institute

⁴ Spill Advisory Group – a non-profit spill response advisory group.

⁵ Spill Control Association of America – a U.S.-based association that promotes the interests of pollution response community.

⁶ Oil spill response equipment manufacturer

⁷ Petroleum exploration, extraction, shipping, refinement, and sales company.

⁸ Spill response company that is hired by petroleum companies to plan and execute spill response efforts.

Durability

Determining burner durability requires a great deal of careful engineering that is not within the scope of this program, but is not impossible. There are published methods for simulating engine or burner heat transfer conditions on material test coupons to measure their thermal deformation, corrosive erosion, and creep in gas turbine engines [16,17], but those burners are exposed to much less salt. A better analogy is coal or biomass burner corrosion [18,19]. The generally accepted methods for predicting corrosion is to expose coupons of candidate materials to the temperatures and corrosive chemicals to document and measure corrosive erosion. Structural simulations are then conducted to using the measured temperatures and corrosion rates to determine material temperatures, thermal strains, and their effects on the fatigue and deformation over time and their impact on life. It is not a simple project, but there are companies that specialize in such tasks for supporting the coal and gas turbine industries.

Minimum Burner Size

The initial test burner used a 12.7 mm (0.5 in) atomizer and all of the burner components scaled from that dimension. A smaller burner could be built, but the flow rates would scale as described in Burner Operational Specifications. Likewise, the reduced radiation produced may produce a dirtier burn.

Maximum Burner Size

The maximum burner size is probably limited more by the available air compressor size than the possible size and available oil pump size. Again, the reader is referred to the discussion in Burner Operational Specifications. There are some logistical concerns in terms of weight, mounting, and transport for a very large burner. There is likely an appropriate compromise in size that allows for transport and modularity while still maintaining throughput and effectiveness.

Compatible Oil Type

Besides a few witness tests with light distillates, only crude oil and crude oil emulsions have been tested in the burner. Participants in the 30 March 2022 demonstration asked whether refined or residual fuel oils, such as marine diesel or intermediate fuel oils (e.g., LS or IFO fuels) had been tested. That was not within the scope of the current program, but could be tested if mandated by the sponsor agency and a subsequent agreement with NRL.

There are some aspects of such burn tests that should be discussed. First, both diesel and intermediate fuels contain heavier constituents and may require pilot torch adjustments, but there is no reason to suppose that once ignited, these fuels will not burn. Previous burn test with Oriente crude oil, a mid-weight crude, were successful [1,2].

Spare Parts Package

One of the demonstration participants asked about what we thought would be included in the spare part package. This is a fairly advanced engineering question, but we speculated that given the cool operation and resulting durability by the atomizer and the hot corrosion observed with previous burner shrouds, that the burner shroud components would be the first to be damaged beyond operability. Auxiliary equipment spares, such as hoses and mounting straps, should also be maintained, but that is not a detail we have been mandated to explore.

Burner Orientation

One of the aspects of burner operation that has not been explored was the influence of burner orientation on its operability. This topic was discussed after suggesting that the burner be oriented at 90° from vertical, facing outward from a ship's or oil platform's deck with the burning plume extending over the water. This would need to be tested on land first; testing over the water would likely require more extensive permitting. The main questions would be effectiveness (is the behavior altered) and hazard mitigation (is there more likely to be a spill, etc). It may be found that an angled or horizontal orientation is preferable, at least for some scenarios.

Spill of Opportunity

One of the participants at the public demonstration suggested that a small number of burner packages be assembled that could be rapidly assembled and used in a spill of opportunity to verify and validate the burner's effectiveness and performance. Each package would be composed of a burner, the requisite components, and necessary peripherals all packed into a shipping box for rapid deployment. The diesel-powered air compressor, hydraulic power unit, and hydraulic pump are the most expensive components of the system and would need to be rented on short notice for a spill.

TECHNOLOGY TRANSITION

The technology transition describes the process by which the burner design is adopted by a company or government organization for manufacture, the associated system is integrated into a larger spill response system and management plan, marketed for distribution, and used by the oil spill community for salvage and spill operations in both demonstration and application roles. There are many details for each of these to occur that are outside the scope of this program and expertise of the authors. A handful of the more prominent aspects will be described, including market demand and intellectual property.

The first consideration for this technology and its transition is a market application and demand for use in oil spills. As of the writing of this report, the immediate demand for this burner has been brought forward by government or commercial interests. While the use case is clear to most relevant entities, there has not been a spill or salvage effort that has required its use. One of the ideas brought forward was to assemble a demonstration, practical-scale equipment package of the burner and its peripheries for use in a "spill-of-opportunity." Such packages could be built and stored in a small shipping container for transport to a spill. Demonstrating the usefulness of the burner in real spill scenario would embolden spill response planners, oil spill response practitioners, and then manufacturers to invest money in the final stages of burner development that are necessary for it to be used in a practical manner.

Either during demonstration efforts or after the technology has been successfully demonstrated, local and federal agencies must provide guidance and permitting for use of this low-emission burner. This report will hopefully provide information that may inform future demonstration efforts and policy decisions, with the hope that either a government agency or a company takes the design and fields it.

There is not a significant amount of intellectual property involved with the burner design, except for the atomizer. The shroud design adopts typical burner design attributes, such as a flat inlet bulkhead and sudden expansion surrounding the atomizer, that is typical to both industrial and aviation gas turbine engines. The holes in the shroud that aid in the entrainment and mixing of cooler air with the burning fuel are also typical of gas turbine engine design. The novel component of the burner system is the atomizer, which is a modified version of the flow-blurring atomizer [5,7,20,21] that increases turbulent mixing between the

spray plume and the surrounding air to shorten the burning plume and decrease pollutant formation (U.S. Patent App No 17/343,846). Though a conventional flow-blurring atomizer could be attempted, it has not been tested with the burner and is presumed to produce a dirtier flame. Therefore, whomever sells the burner will need to negotiate licensing with NRL for that atomizer.

Continued development of the burner is at a stage that the rest of the design issues can be resolved outside of NRL, should a private company wish to shoulder them. Designing the thermal management of the burner, its surrounding, and supporting structures, could be done fully by NRL, but whomever manufactures, distributes, specifies its use, and the final users should have the best understanding, control, and design of those details. NRL does not intend to do those tasks.

At this time, the NRL Technology Transfer Office and Techlink (points of contact Holly Ricks-Laskoski and Micaela Whalen, respectively) are in charge of negotiating non-disclosure agreements and publicising details about the burner, including intellectual property. The authors' role is almost entirely technical in supporting the technology transition efforts.

FINANCIAL SUMMARY

This program was funded for \$750,000 for year one of this program and \$476,076 for year two. Dr. Tuttle and Mr. Pfutzner were assigned approximately 50% and 75% full-time equivalent both years, which resulted in approximately \$450,000 labor spent per year. Travel for testing and presentations accounted for \$20,000, plus an additional \$110,000 for NAVSEA's SUPSALV crew to bring and operate equipment for testing. Money was originally allocated for use with NSWC Dahlgren's drone operations group to aid in emissions testing. This did not occur (instead performed by EPA). Approximately \$6,000 was unused. The rest was spent on materials for creating the prototypes, the plumbing, auxilliary equipment, and maintenance items.

CONCLUSIONS

NRL has successfully completed several technology development and demonstration tasks to mature the NRL/BSEE emulsified crude oil burner system and to initiate technology transition efforts. These efforts have included component and subsystem development, system development, and technology transition efforts.

Critical components have been matured and verified, including the ignition torch. Critical component engineering data, including burner and deck temperature and heat transfer data, have been collected. These data will allow component and burner integration engineers to design, adapt, and integrate the burner into existing shore and ship-based approaches to using the burner. Atomizer operability has been demonstrated for the 25% and 50% scale burners, but there is no reason to suggest that the larger atomizer will not be able to generate sprays with ignitable spray diameters. Burner material options were examined, and two approaches are suggested: for inexpensive, short-life burners, AISI 300 series stainless is a reasonable material choice. For long duration use with high emulsion fraction or with more operation cycles, Inconel HX is a good compromise in duration and cost.

System-level development efforts have included an emissions measurement study performed in collaboration with the EPA, a mounting and wave motion study performed at Ohmsett, a debris study, and a public demonstration for government agencies and private companies. The emissions study successfully demonstrated exceptionally high combustion efficiencies (99.8%) for a range of flow rates, oils, and

emulsion fractions. These data overwhelmingly show that the burner can dispose of crude oils more cleanly than in situ burning and at efficiencies that would be acceptable to many state and federal agencies that govern air quality.

The mounting and wave motion study at Ohmsett was used to examine how the burner might be mounted to a SUPSALV P06400 Modular Working Platform and how the spray might behave when the platform was exposed to rough ocean conditions. We observed that the burner did not experience structural failure and the spray plume did not impinge against the burner shroud during wave motion. This means that the burner can be used at realistic conditions on the ocean without risking unburned or burning spray from exiting the shroud and landing on a supporting deck.

A public demonstration on 30 March 2022 was performed before many governments agency and industry personnel to investigate how the burner might be integrated into current spill control planning, equipment inventories, and management efforts. These demonstrations have initiated ongoing technology transition discussions.

FUTURE WORK

As with any technology development efforts, there are aspects that could be further refined and validated. These include testing a broader range of oil chemistries or oil weight ranges, the influence of cold weather, burner orientation, and prototype systems for a spill of opportunity.

The interest in additional oils is driven by the potential use of the burner to dispose of ship fuel for both spills and salvage operations. In such cases, the fuels are composed of either distillates, residuals, or blends of both. These fuels typically are either mid-weight distillates, such as diesel fuel, or are distillation residuals that have had their light and mid-weight constituents distilled out and a limited amount of mid-weight constituents added to keep viscosity within specification limits (e.g., IFO 180, 380, VLSFO, etc.). Such fuels have not been tested in the NRL/BSEE burner, so there is a clear motive to verify that such fuels can be ignited, even if much higher pilot gas burn rates are necessary to ignite and anchor their combustion.

Another operability concern that could be tested was cold weather or Arctic operability. The primary potential limits to cold weather operability would be increased oil viscosity, which should increase pumping pressure drop, produced larger atomized droplets [8], and require higher ignition heat. The higher pumping pressures from higher viscosity fuels could be examined, but that is not directly related to the burner since it is a general challenge of all oil-handling equipment in the Arctic. The larger spray diameters and higher ignition heat associated with Arctic temperatures are analogous to the more viscous, heavier fuel oils mentioned in the preceding paragraph so can be tested by increasing fuel viscosities. Finally, it should be noted that the burner in its current form has been tested at temperatures near freezing in the past, but it has not been tested in Arctic conditions. Such testing would require that the burner and the necessary infrastructure be transported and installed at a cold weather burn test site, such as Poker Flats in Alaska or CRREL in New Hampshire.

One of the application variations that could also be verified is testing the burner at 45° or 90° from vertical so that the exhaust plume and any incident radiative heat transfer would be directed away from a vessel and out over water. These orientations could be tested at NRL-CBD by placing and fixing the current 50% scale burner on specialized temporary mounting stands.

As discussed in the Spill of Opportunity section, we could also build a number of packaged demonstration burner systems that could be stored near the Gulf of Mexico, in Alaska, or off the Pacific Coast for deployment during an actual spill. Such an effort would require a sizable investment in equipment and its storage, as well as the labor and travel for NRL personnel to support the use of one or more of the demonstration burners in an actual spill.

Though these potential continued efforts are intriguing, continued funding of the burner development depends on the interest of BSEE, other government agencies, and the spill response industry in using the burner for spill remediation. The spill community has generally been aware of this technology since NRL gave a small presentation about the burner at the 2017 IOSOC. Since that time, there has been many discussions, NDAs have been signed between NRL and various companies, and there have been public demonstrations and discussion but no single company has yet been willing to start the process of market analysis and system testing on their own. This suggests that there are barriers to adopting the burner that are not being brought forward and that manufacturers view the burner as too risky or too expensive to invest in the final development. The concept of assembling a small number of packaged demonstration burner systems is one way to build confidence with potential end users.

ACKNOWLEDGEMENT

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PERSONNEL

The Navy Technology Center for Safety and Survivability of the Naval Research Laboratory has an established history of successfully supporting the combustion and fire testing of the Navy's facilities and operations.

Dr. Steven Tuttle is a Mechanical Engineer and Section Head in the Combustion and Reacting Transport Section of the Navy Technology Center for Safety and Survivability (NTCSS) at the U.S. Naval Research Laboratory (NRL). Dr. Tuttle worked in the gas turbine industry for seven years while managing and conducting his doctoral research at the University of Connecticut. As an engineer, he developed and validated heat transfer, thermoacoustic, and spray combustion stability models for main burners, afterburners, and nozzles in the engine technology development and demonstration organizations. At the same time, he directed and managed funding to the University of Connecticut that supported his research and that of others. As a student, he designed and built an afterburner combustion experiment and the associated electronic fuel control and safety systems. For his postdoctoral studies, he was the principle investigator for velocity measurements of a reacting scramjet cavity and shear layer at the U.S. Air Force Research Laboratory. He joined the staff at NRL in 2011, where he has been the principle investigator of Department of Interior-sponsored programs examining combustion behavior of emulsified crude oil slicks and sprays. He also collaborates with other NRL investigators in projects ranging from novel fuels to fire characterization and instrumentation.

Mr. Christopher J. Pfützner is a Mechanical Engineer in the Combustion and Reacting Transport Section in the Navy Technology Center for Safety and Survivability (NTCSS) at the U.S. Naval Research Laboratory. Mr. Pfützner has worked in a technical capacity with an oil and gas blending company in Houston, Texas, in addition to working in the refrigeration and automotive industries since 2009. At Colorado School of Mines, he studied Mechanical Engineering, contributed to research involving heat

transfer and oxidation in concentrated solar cells, and managed the school's battery-electric vehicle efforts throughout its lifecycle. He joined NRL in 2017 and serves in various design and test engineering roles in support of internal and external programs.

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APPENDIX I

Graphical abstract of low-emission crude oil burner is shown in Fig. A.1.

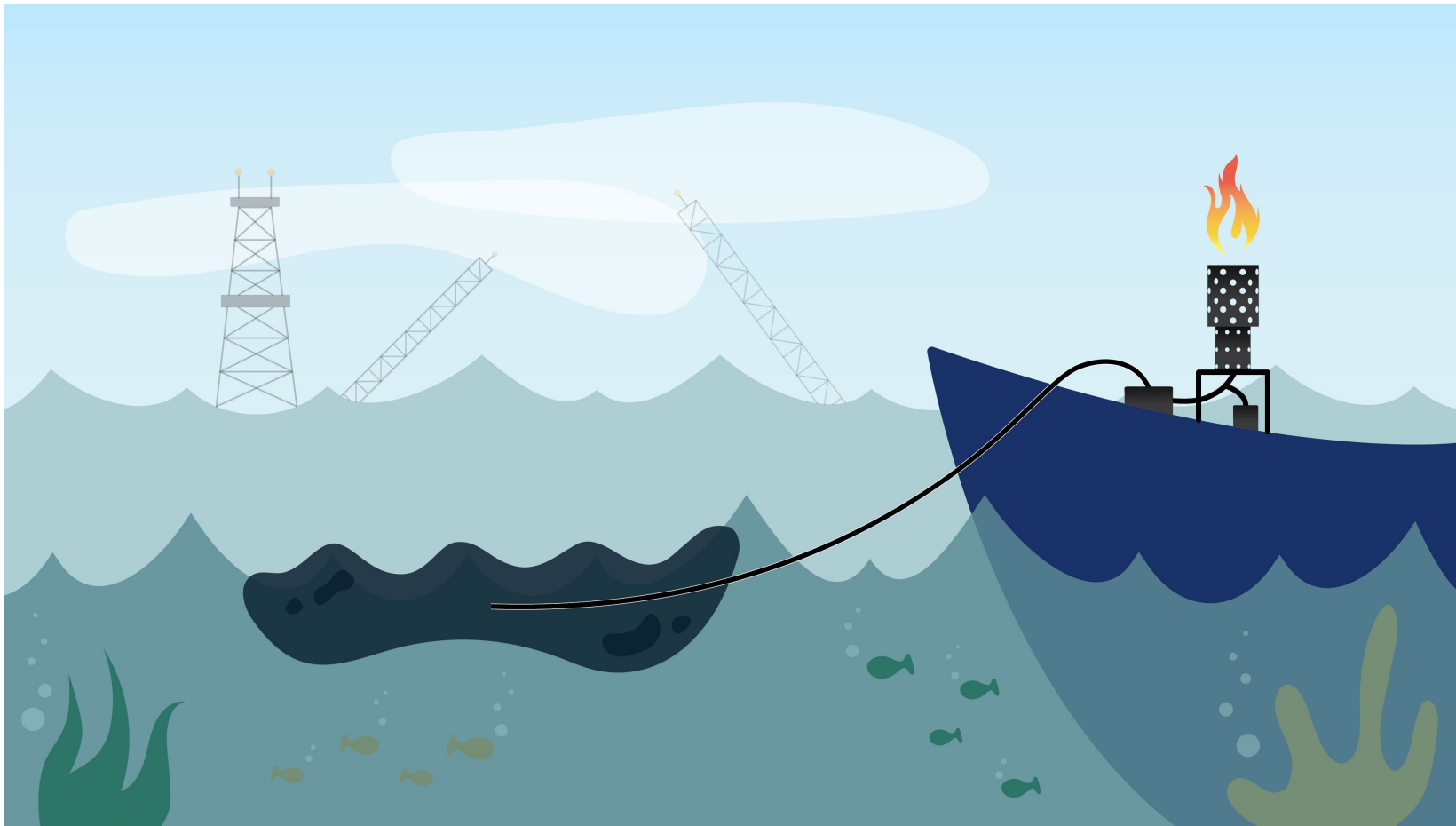


Fig. A.1 - Graphical abstract of low-emission crude oil burner. Credit Sarah Peterson, Naval Research Laboratory.

APPENDIX II

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Low-Emission Crude Oil Burner Manual and Specifications

US Naval Research Laboratory, Code 6185
Rev Number 001 – 10 November 2021



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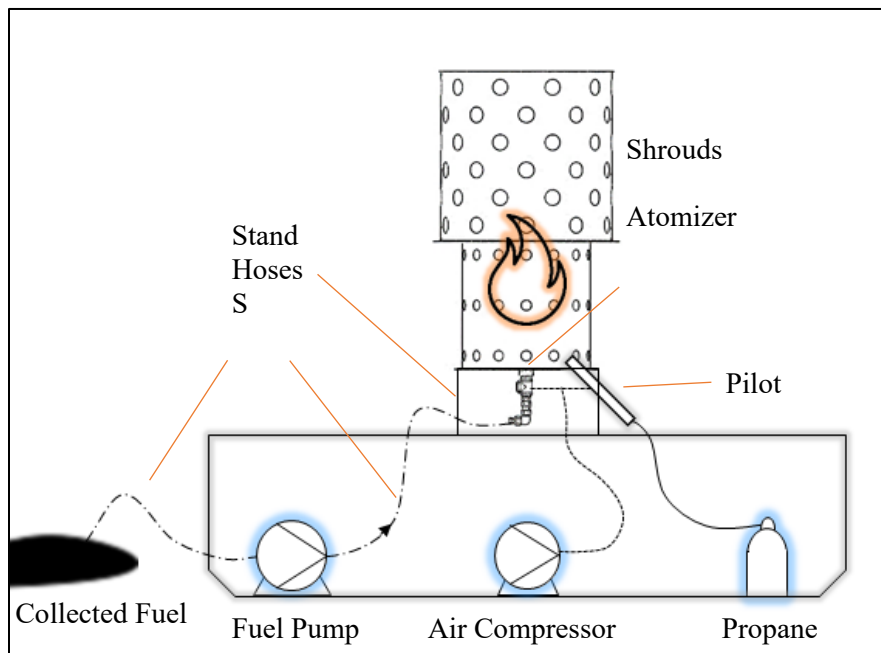
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Overview

This document details a low-emissions burner that can be used to remove fuels from spill sites. It is designed to cleanly and quickly burn fuels such as crude oil, including after they have been lightly weathered and, if at sea, emulsified with water. The burner is lightweight and interfaces with off-the-shelf pumps and air compressor equipment, so once spilled fuel is collected, it can be pumped to the burner onsite. This includes remote areas offshore, as well as near population centers and fast water where spills must be remediated cleanly.

Equipment

- Burner Atomizer
- Burner Shroud
- Burner Stand
- Burner Pilot Torches
- Pilot Torch Fuel (Propane)
- Air Compressor
- Fuel Pump
- Hoses
- Air and Propane Regulators (not shown below)



Specifications

Note that this burner is a working prototype, and some specifications may change as future variants are changed.

- Dimensions:
 - Assembled Height (with Shroud): 11 ft
 - Assembled Height (with Shroud and Stand): 14 ft
 - Diameter (with Shroud and Stand): 5.5 ft
 - Dry Weight (with Shroud): 850 lb
 - Dry Weight (with Shroud and Stand): 915 lb
 - Burner Atomizer Diameter: 2.0 in
 - Shipping weight depends on auxiliary equipment chosen.

- Fuel Flowrates:
 - Minimum Fuel Flowrate: 3 GPM *
 - Maximum Fuel Flow Rate: 640 bbl/day *
 - Atomizer Exit Pressure: 45 psig

- Equipment Requirements:
 - Minimum Required Air Flow: 250 SCFM *
 - Maximum Air Flow: 910 SCFM *
 - Pilot Torch Fuel: Propane
 - Pilot Torch Fuel Flowrate: 0.2 SCFM **
 - Optimal air flow depends on fuel and water loading.
 - Electrical need depends on pump and air compressor used.

- Operation:
 - Maximum Tested Wave Conditions: Beaufort Sea State 2
 - Maximum Tested Wind Conditions: 15 mph
 - Maximum Designed Wind Conditions: 35 mph ***
 - Maximum Debris through Atomizer: 0.2 in****

 - Maximum Emissions PM2.5: 40 g/kg_{oil}
 - Average Emissions PM2.5: 15 g/kg_{oil}

 - Maximum Emissions CO₂: 2850 ppm
 - Maximum Emissions CO: 2.0 ppm

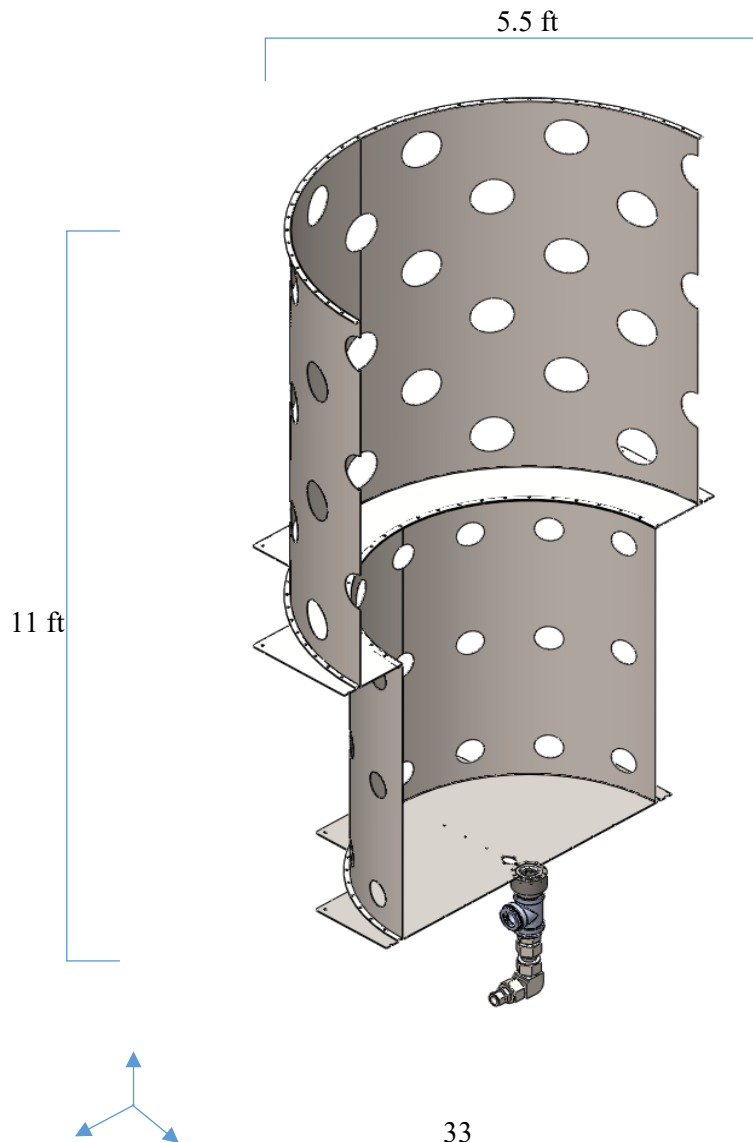
- Average Modified Combustion Efficiency: 99.8%

* Numbers are for medium weight crude oil, and will differ depending on viscosity and water content.

** Achievable with any commercial off-the-shelf propane tank.

*** The burner should only be run when it is safe for personnel to be present.

**** Hoses and pump are usually limiting factor



Safety

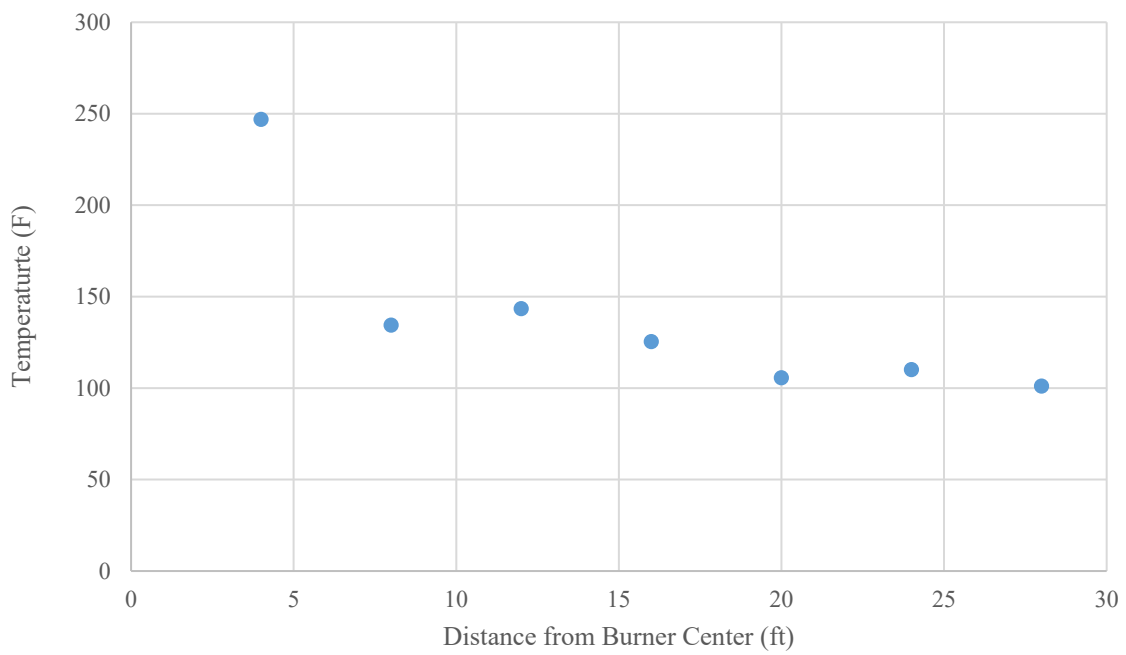
This burner creates a very hot flame in order to release very low emissions. General guidelines are presented below, but the operator is urged to take all available precautions when dealing with flammable fuels and open flames.

- Number of operators: 1
 - Recommend having an additional person as backup and firewatch.
- Minimum Safe Distance (without PPE): 100 ft
- Minimum Safe Distance (with PPE): 30 ft no time limit
 - Recommended PPE:
 - Safety Glasses
 - Flame Resistant Coveralls
 - High-traction safety toe boots
 - Helmet

Distance from Burner Center (ft)	Temperature (°F)	Heat Flux (kW/m ²) at Floor
4	245	2.0
12	150	0.75
20	105	0.25

- Hearing protection
- Heat radiation is highest above the shroud. Keep personnel and equipment away from flame.
 - See figure for more detail
- Minimum distance for pilot torch fuel: 100 ft
- Minimum distance for pump: 30 ft unless pump rated for high temperature.
- Minimum distance for air compressor
- Required hose material: Solvent-safe rubber (CR and/or NBR recommended)
 - Check hoses for cracking and melting before operation and every 10 hours
- Expected emissions and soot:
 - Based on measurements, high water content (greater than 20% by volume) will likely result in double the PM2.5 emissions content as compared to neat (0% water) flow.
- Hoses and small pump equipment can create a tripping hazard.

Temperature v Distance at Full Flow
(measurement height 4 ft below atomizer exit)



Standard Operating Procedure

Preparation:

- Abide by local fire protection protocols and assign a qualified firewatch.
- Determine if weather is safe to operate in for all personnel.
- Secure burner and all auxiliary equipment to mounts and use enough hose length to allow movement between equipment as needed, especially if at sea.
- Orient burner as close to vertical as possible. It will burn at an angle but this generally makes it more difficult to secure and predict the heat affected zone. Do not position anything above the burner, as this is where the heat is highest.
- Clear combustibles and unnecessary personnel within 100 ft.
- Check that all shutoff valves can open and close smoothly.
- Attach all hoses.

Startup:

- Ensure all fuel supplies are shut off.
- Position a standard hand torch with at least a six-inch nozzle next to one of the propane pilot torches and light it.
- Open the propane fuel supply until the pilot torch lights. Depending on wind, both pilot torches may need to be ignited separately.
- Open the air supply slightly (<10 SLPM or ensure that the air does not extinguish the pilot torches).
- Start pumping fuel slowly (<10 GPM to start) until ignition occurs.
 - If ignition does not occur within 60 s, shut fuel and air off and check that pilot torches are lit
- Ramp up fuel and air in “steps” of about 10 GPM fuel until flame is clear of soot and stable. These steps can be done fairly rapidly.

Shutdown:

- Turn off fuel supply, then air, and then propane supply.
- Allow to cool before removing hoses or moving the burner.
- It can be cooled quicker by spraying it with non-salt water.

Modifications

The ignition system can be modified to use gas (propane) or liquid (diesel or jet) fuel. Gas does not pose a spill risk and is preferred, but some operators may find liquid to be more appropriate in some environments. Larger (higher heat) pilot will provide better ignition for heavier and more emulsified fuels. This would require higher pilot fuel flow.

The atomizer can pass through sizable (0.2 in) debris, but requires suitably large pump and hose capabilities. Higher range of debris may be possible but is untested.

Shrouds may not be necessary depending on ambient wind and proximity to combustibles and personnel. The shrouds do provide air mixing and alter the air flow.

Multiple burners may be run simultaneously, although this has not been tested.

High viscosity (>1000 cP) fuels may require special pump equipment and reduced flowrates.