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Bureau of Safety and Environmental Enforcement (BSEE) Report: Interface Insulations Systems for Enhancing in-situ Burning

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EXECUTIVE SUMMARY

In-situ burning is an effective oil spill response technique, but drawbacks include emissions of combustion products and particulates to the air, and the requirement to collect residual unburned oil. Reducing emissions during a burn and the amount of residue remaining after a burn would significantly improve the usefulness of in-situ burning. This study investigated three novel concepts to alter the oil/water interface beneath a burning oil slick on water, to reduce the amount of residue remaining after extinction, and prevent the residue from sinking. The effects of the interface concepts on emissions from the in-situ burns was investigated by the U.S. EPA under a separate contract.

Small-scale test burns with currents and waves were completed at the SL Ross Environmental Research Limited. (SL Ross) laboratory in Ottawa, Ontario. Three concepts for altering the oil/water interface during a burn were tested:

- Hollow aluminium spheres
- Carbon fiber cloth mats
- High-temperature silicone rubber sheet

The aluminum spheres had a negative effect on burning efficiency, likely due to conducting heat from the oil layer into the water. Significantly smaller metal or glass spheres (on the order of 2 to 3 mm diameter) that would remain entirely within or above the oil layer may be a superior configuration for this concept.

The silicone sheet performed satisfactorily in calm conditions but disrupted the oil slick in waves, which negatively impacted the burn efficiency. In calm conditions, maintaining the sheet at a shallower depth than what was used during these tests (i.e., 3 cm) may be advantageous in inducing a vigorous burn phase, but this may result in damage to the silicone sheet from exposure to higher temperatures. An insulating material with a higher thermal tolerance may perform better.

Tests with the carbon fiber mats were the most variable in burn efficiency results. Some of the replicates showed significantly higher efficiencies than the control burns, while the mats were less effective in other tests at the same current and wave conditions. Review of the test videos determined that when the carbon mat was on top of the oil layer, with some wrinkles protruding above, that there was a wicking effect that maintained the burn for longer and significantly reduced the amount of residue.

One test with a rubber mulch was conducted and the results showed an improvement in burn efficiency over the control burns that was comparable to the best tests with the carbon fiber mats.

Large-scale test burns were conducted at the Cold Regions Research and Engineering Laboratory in Hanover, New Hampshire. The objective of the large-scale test was to evaluate the effects of scale on the performance of the selected interface insulation concepts.

Tests were done with carbon fiber mats applied both before and after oil was deployed. Tests were also done with a granular rubber. The carbon fiber when applied before the oil did not have a significant effect on burn efficiency compared with the control burns. The carbon fiber applied after the oil had a

negative effect on burn efficiency. Observations indicated that the oil did not readily migrate through the fabric. It is recommended that future testing of this concept use a more permeable fabric that would allow the oil to penetrate through, and a support structure that would keep the fabric at the surface of the oil layer.

Crumb rubber had a modest positive effect on the burn efficiency compared with the control tests when applied at a ratio of approximately 10% of the mass of the oil. Further testing of this concept could lead to additional improvements in burn efficiency. An alternative product to crumb rubber, with similar density and thermal characteristics, should be investigated.

In general, it was found to be difficult to place a rigid material (such as the silicone sheet) in a moving current and hold it at the right location indefinitely. Similar difficulties were encountered with the low-permeability carbon fiber cloth deployed before the oil; the current would push the cloth down about 5 cm below the oil where it had little effect on the burn. A fluid material, such as the aluminum balls and crumb rubber, was easier to deploy and hold in position provided the material had a density less than water and close to that of oil.

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1. INTRODUCTION

In-situ burning of crude oil on water can rapidly remove significant amounts of oil from the marine environment; however, this combustion technique results in burn residues and black carbon soot from unburned oil and incomplete combustion. Some residues have the potential to sink, which could impact benthic organisms, and burn emissions may cause public concern about air quality. Anecdotal evidence from past burns in fire-booms where unburned oil and residues were combined and reignited to remove additional volumes suggests a potential technique to improve burn efficiency; however, residues from conventional in-situ burns can often be difficult to collect.

1.1 BACKGROUND

To burn oil spilled on water, three elements must be present: fuel, oxygen, and a source of ignition. Combustion is a vapor-phase phenomenon and the oil must be heated to a temperature hot enough to supply vapors at a rate sufficient to support continuous burning (the Fire Point). The key oil slick parameter that defines whether the oil will burn is slick thickness; if the oil is thick enough it self-insulates and keeps the burning slick surface at a high enough temperature by reducing heat loss to the underlying water.

Figure 1 illustrates the heat and mass transfer processes that occur during the in-situ burning of an oil slick on water. The key driving process is radiative heat transfer from the flames back to the surface of the slick. Some of this heat is used by vaporizing the liquid hydrocarbons which rise to mix with air above the slick and oxidize - or burn; the remainder transfers through the slick to the underlying water. Once ignited, a burning thick oil slick reaches a quasi-steady-state in which the vaporization and burning rate sustains the necessary heat transfer back to the slick surface.

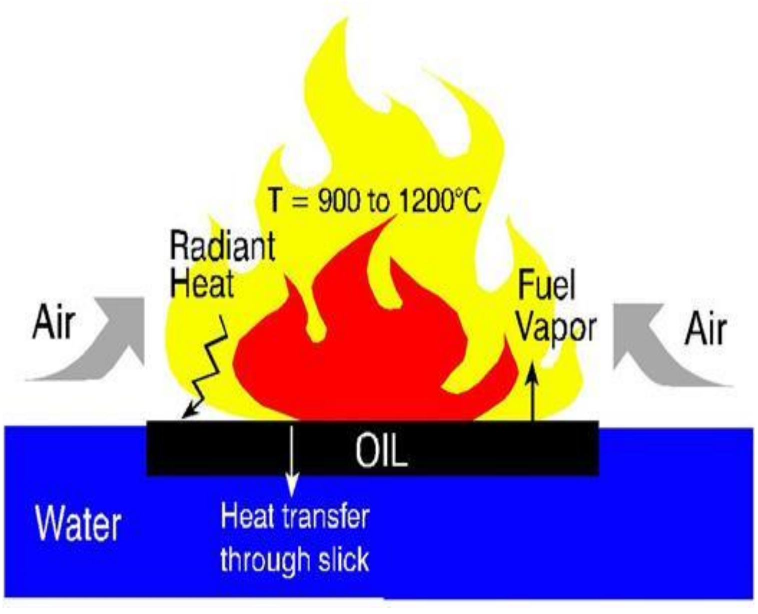

Figure 1: In-situ Burning Heat and Mass Transfer Processes

Extensive R&D in the 1980s and 90s showed that the process by which oil vaporizes is not a distillation (whereby the lightest, most volatile components are vaporized first followed by progressively heavier, less volatile components) but is closer to an Equilibrium Flash Vaporization (EFV) in which vapor of essentially constant composition over time is produced by boiling liquid oil of essentially constant composition (Buist et al., 2013; see Figure 2). This results in near-complete vaporization of successive surface layers of the oil slick with minimal mixing and heat transfer to the underlying oil and/or water layers. It is believed that *Imperfect* EFV occurs during in-situ burning because the hot flames and the insulating characteristics of the oil combine to create high heat inputs to the oil surface layer and high surface temperatures in a layer known as the "hot zone". The temperature of this hot zone is insufficient to vaporize all the hydrocarbons in crude oil: the heaviest and least volatile end up being concentrated in the residue, which slowly increases in density and Fire Point.

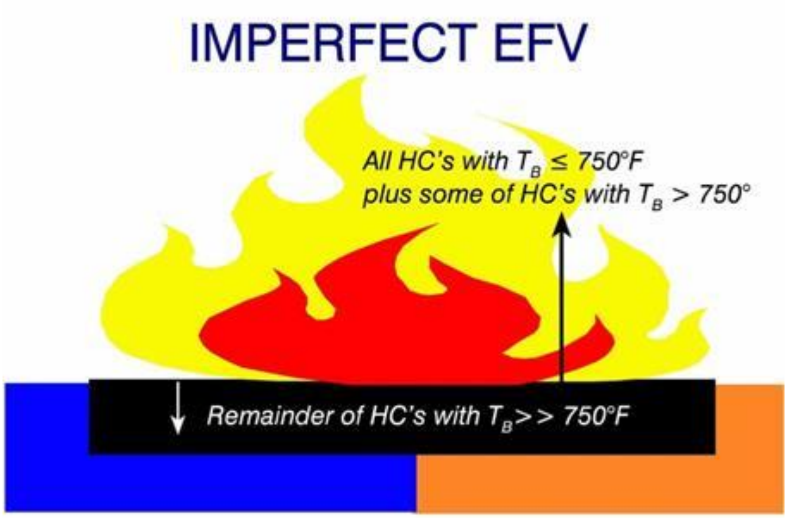

Figure 2: Imperfect Equilibrium Flash Vaporization

As the slick thins, increasingly more heat passes through it to the underlying water. Eventually enough heat is transferred through the slick to allow the surface oil temperature to drop below its current Fire Point and burning stops (Figure 3). Oil removal efficiency (or burn efficiency), the percentage of the original oil that is remaining after the flame extinguishes, is primarily a function of three factors: the initial thickness of the slick; the thickness of the residue remaining after extinction; and, flame coverage of the slick.

As the burning slick thins, the "hot zone" approaches the underlying water surface and increasing amounts of heat are transferred into the water column. This process is illustrated in Figure 4. As the rate of heat transfer increases, the temperature of the layer of water directly beneath the slick increases. The presence of the oil layer allows the water to be heated above its boiling point (superheating) and once a temperature of approximately 120°C is reached, the water begins to boil violently. The generated steam vigorously mixes the remaining oil layer and ejects oil droplets into the flames. This temporarily results in increased burn rate, flame height, and radiative output.

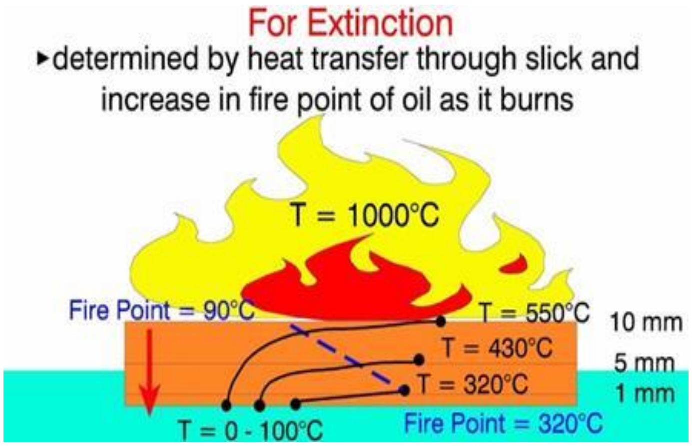

Figure 3: Extinction of an In-situ Burn

The onset of a vigorous burn phase has never been observed in a towed fire-boom (i.e., at the *Exxon Valdez* test burn, the Macondo burns, or any experimental burn in a towed fire-boom) or a burn in currents, likely because water flow under the burning slick prevents the water from heating enough to boil.

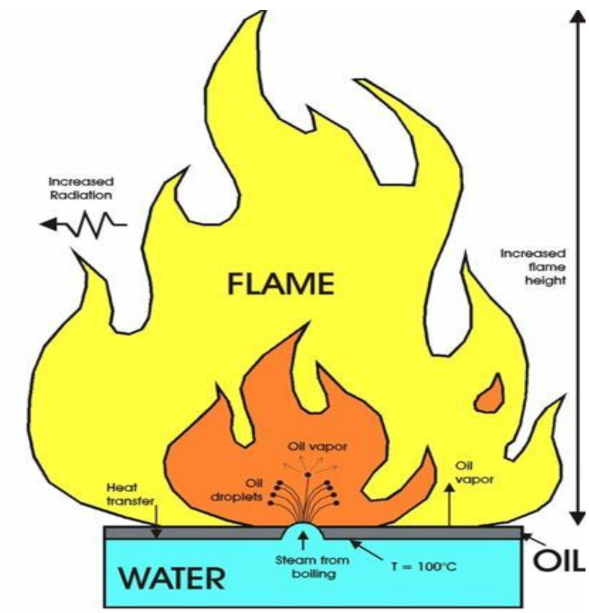

Figure 4: Development of the Vigorous Burn Phase

1.2 Objective

The heat transfer through the slick in the final stages of the burn controls the amount of residue and whether a vigorous burn phase occurs. Reducing the heat lost to the underlying water by inserting some form of insulation could potentially allow the burn to continue longer than it otherwise would and reduce the amount of residue. The objective of the project was to evaluate three concepts for an insulating layer at the oil/water interface that may accomplish this.

The project also presented an opportunity to investigate the effects of the insulation concepts on emissions, in the hopes of measuring a reduction. The U.S. Environmental Protection Agency (U.S. EPA) sampled the plumes from in-situ burns conducted in the latter phase of the project under a separate contract with BSEE.

2. Small-scale Tests

The first phase of the project involved conducting small-scale in-situ burn experiments on water with the three different interface insulation concepts in the SL Ross wind/wave tank. The objective of the small-scale experiments was to simulate in-situ burning conditions with waves and water movement relative to the oil slick, and measure the effect of interface insulation materials on burn efficiency.

2.1 Apparatus and Materials

The experimental apparatus, including test tank, containment boom, test oils, and interface insulation materials is described below.

2.1.1 Test Tank

The small-scale burns were conducted in the SL Ross wind/wave tank, which measures 11 m long, by 1.2 m wide. The tank was filled with fresh water to a depth of 86 cm and remained at a temperature between 14 and 17°C during the tests. A fume hood connected to a high-capacity fan was positioned above the area where the burns were conducted to collect the smoke and emissions and exhaust them to the exterior of the building. Galvanized steel sheets were installed along the sides of the tank in the burn area to protect the tank from the heat. The sheets were actively cooled during the burns with water recirculated from the tank. The exterior of the burn area of the tank is shown in Figure 5.

Figure 5: Burn area with fume hood, heat shields and trolling motors.

A false floor measuring 2.5 m long was constructed in the burn area of the tank at a depth of approximately 40 cm. The false floor enabled creating a recirculating current in the tank. Two electric trolling motors (Minn Kota Endura C2) were installed at the beach end of the tank (the left side of Figure 9), with the propellers projecting below the false floor directing current towards the wave paddle end of the tank. A return current was generated above the false floor in the opposite direction.

The trolling motors had five forward speeds. The current speed generated was measured at each of the speed settings. A plot of motor setting versus return current speed is provided in Figure 6.

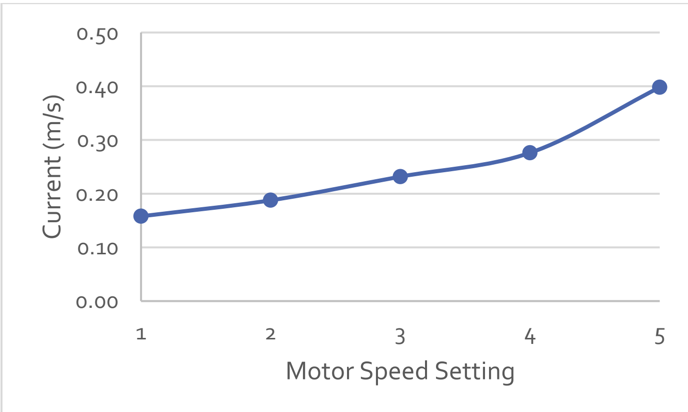

Figure 6: Current speed vs. motor setting

2.1.2 Fire-boom Mockup

An open fire-boom mockup to contain the test slicks was constructed from a 20 cm wide sheet of galvanized steel (1-mm thick), shaped into an approximate catenary (Figure 7). Flotation was provided by four empty 1-gallon paint cans secured to the outside of the boom. The vertical position of the floats was adjusted so that the fire-boom was approximately half submerged in the water (i.e., an equal draft and freeboard). The fire-boom was loosely tethered in the center of the tank, below the fume hood, with light-gauge steel chain to maintain position but allow movement with the waves.

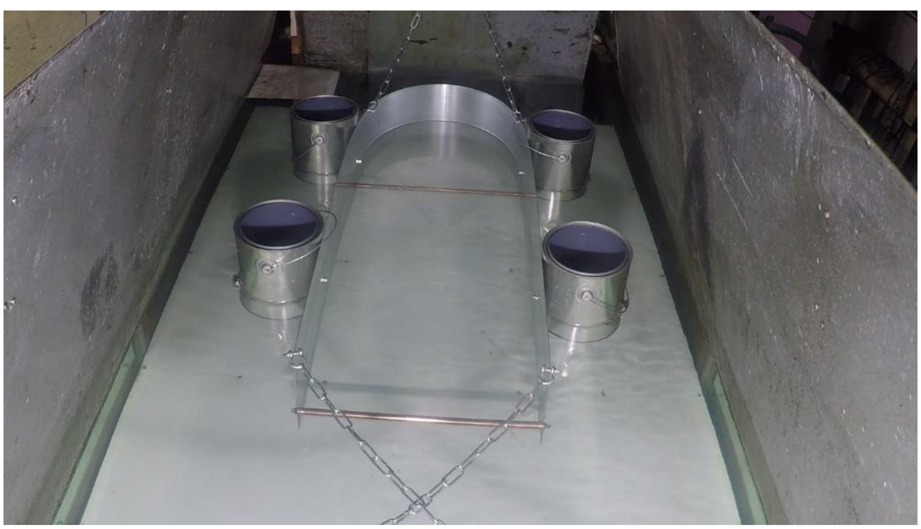

Figure 7: Fire-boom mockup

2.1.3 Test Oils

Tests were conducted with two crude oils from Alaska, Northstar and Alaska North Slope. Both oils were tested fresh (i.e., un-weathered). Selected properties of the oils are provided in Table 1.

Table 1: Selected properties of test crude oils.

	Northstar	*Alaska North Slope*
API°	41	32
Density @ 15°C (g/mL)	821	863
Dynamic Viscosity @ 15°C (cP)	2.1	11
Pour Point (°C)	< -21	-24
Flash Point (°C)	-10	< -15

Initial trials with oil in the containment boom determined that speed settings 1 and 2 on the motors (equivalent to surface current speeds of 0.16 and 0.19 m/s, respectively) were able to keep the oil within the boom mockup. Entrainment failure was observed with the Northstar crude oil when the motors were set to speed setting 3 or higher (current > 0.23 m/s). It was observed that 750 to 1,000 mL of oil produced a slick that remained in the boom at speed settings 1, but that when 1,250 mL of oil was used, the slick extended to the upstream edge of the boom and occasionally small amounts of oil were seen escaping around the leading edges. Based on these observations, it was decided to use 1 L of oil for each test.

2.1.4 Interface Insulation Materials

Three interface insulation materials were used in the tests. Information and specifications from the vendors is provided in Appendix A.

2.1.4.1 Aluminum Spheres

Hollow aluminum spheres measuring 2-in. (5.1 cm) in diameter were the first concept tested (Figure 8). The spheres are manufactured by Custom Ornamental Ironworks Limited, Vancouver, B.C., Canada (Part number 30-815) for use as decorative adornments on fenceposts. The balls are made from 11 -gauge aluminum, with a wall thickness between 0.3 and 0.6 inches (8 and 16 mm).

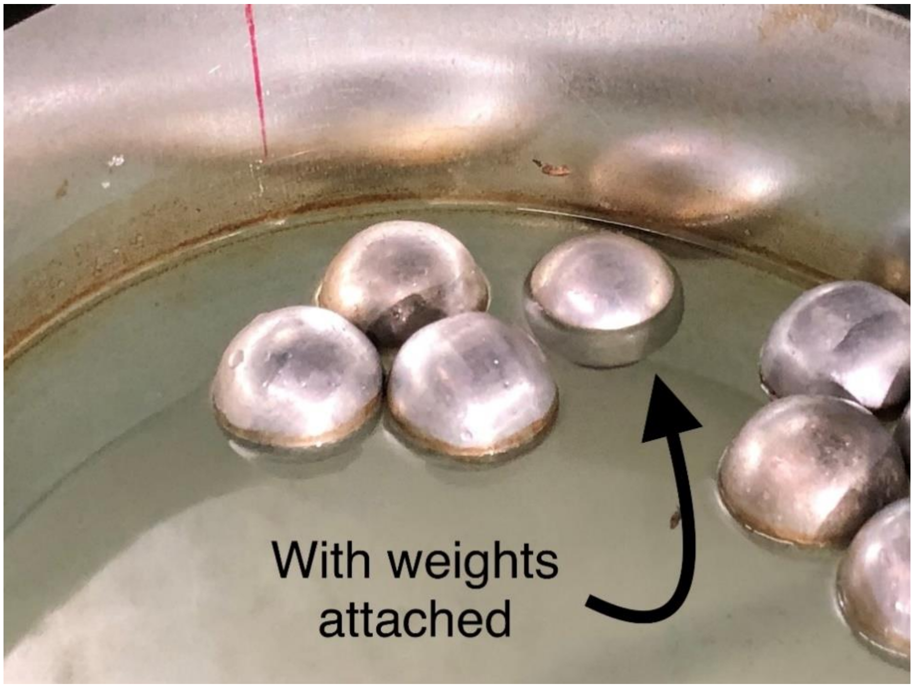

Figure 8: Aluminum spheres

Initial testing showed that the balls were floating high in the water; it was felt that better wicking potential would be achieved with the balls lower in the water. Weight was added to each of the balls by attaching several steel washers to reduce the buoyancy to the desired degree (Figure 8). 48 spheres were used during each test burn. The balls were cleaned after each burn and then reused.

2.1.4.2 High-temperature Silicone Sheet

A sheet of high-temperature resistant silicone rubber was the second interface insulation concept (Figure 9). The sheet was manufactured by E. James & Co. (Model # 2830-1/4C) and measured 91 cm (36 in.) long by 30 cm (12 in.) wide by 0.6 cm (0.25 in.) thick. The temperature rating of the rubber was 204°C (400°F).

The sheet was loosely attached to a metal screen mounted across the fire-boom mockup just beneath the water surface. One end of the silicone sheet was trimmed to conform to the apex curve at the rear of the fire-boom mockup.

Figure 9: High-temperature silicone sheet.

2.1.4.3 Carbon Fiber Mat

A fire-resistant carbon fiber cloth was the third in-situ burning enhancement concept to be tested. The cloth is a carbon fiber weave manufactured by Chapman Innovations (Item No. 222011-100-002-001). The fabric has a nominal thickness of 33 thousandths of an inch, and a weight of 373 g/m^2.

The fabric was purchased as a large sheet; smaller mats measuring 40 cm square were cut for use during the test burns. A new mat was used for each burn; however, it was noted that in most cases the mats appeared to be relatively undamaged and could have been re-used.

Figure 10: Fire-resistant carbon fiber cloth.

2.2 Small-scale Test Matrix

Tests were conducted varying the following parameters: oil type, current speed, waves, and insulation material. The test matrix is provided in Table 2.

Table 2: Small-scale test matrix

Insulation Material	*Oil Type*	*Current Speed*	*Waves*
Control (no insulation) Aluminum Spheres Silicone Sheet Carbon Fiber Mat	Northstar and Alaska North Slope	0.16 and 0.19 m/s	Calm and Regular Waves (Height = 3 cm, Period = 0.8 s)

Two replicates of each test condition were completed. After reviewing the data to that point, one set of additional tests were conducted with the most promising insulation material. In total the test matrix included 72 individual burns.

Four additional burns were conducted following completion of the test matrix shown in Table 2 to investigate additional interface concepts, as follows:

- One test was used to investigate using two layers of carbon fiber fabric, instead of just a single layer.
- Two tests were used with a metal plate installed in place of the high-temperature silicone sheet, to investigate whether simply physically separating the layer of water under the oil slick would be effective in improving burn efficiency.
- One test was conducted with rubber mulch from recycled automobile tires.

2.3 SMALL-SCALE TEST PROCEDURE

Each burn was conducted with 1 L of fresh oil. The oil was measured out in a 1-L beaker, which was weighed before and after the oil was added to determine the initial mass of oil. The fresh oil was carefully poured onto the surface of the water using a metal spatula to distribute it evenly and prevent it from submerging, ensuring that the oil remained within the containment area. The length of the slick was measured and recorded. The temperature of the water in the tank and the ambient air were also recorded.

The oil was ignited using a propane torch. The burns were conducted using fresh oil, so complete ignition occurred almost instantaneously. Once ignited, the exhaust fan was engaged and operated until the burn extinguished. A stopwatch was used to time the burn duration. The tests were also recorded using a digital video camera.

After the burn extinguished, the exhaust fan was shut off, and the residue allowed to cool. The residue was collected using pre-weighed sorbent pads. The pads were hung on a drying rack and allowed to dry for a minimum of 18 hours, to remove any water clinging to the pads. After drying, the pads were weighed to determine the mass of residue.

For the tests with aluminum spheres, oil adhering to the spheres was removed by hand-polishing with the pre-weighed sorbents. For some tests with the high-temperature silicone sheet, some oil was observed to escape from the rear of the boom. This oil was collected separately with pre-weighed sorbent pads, using the same procedure described above. This oil was also considered to be residue for the purposes of calculating efficiency. For the tests with the carbon fiber mats, the mats were weighed before and after the burn (after cleaning and drying overnight to allow water to evaporate) to account for oil residue retained.

2.4 SMALL-SCALE TEST RESULTS

The results of the small-scale test burns are summarized in this section. The complete test results are provided in Appendix B.

2.4.1 Control Burns

Control burns with no insulation material were conducted with Northstar and ANS crude oils, varying current speed and waves. Two replicates of each test condition were completed. The burn efficiency results are provided in Table 3.

Table 3: Small-scale burn efficiency results (mass percent removed), control burns.

Current	*Waves*	*Northstar R1*	*Northstar R2*	*ANS R1*	*ANS R2*
Low	No	65	67	68	67
	Yes	65	66	58	61
High	No	65	71	75	80
	Yes	65	67	70	69

Burn efficiency varied between 65 and 71% for Northstar, and 58 and 80% for ANS. In general, the repeatability between replicates was very good, with an average difference of 3%. The largest difference between repeats was measured with high current and no waves, with a difference in efficiency of 7% for Northstar, and 5% for ANS.

Higher current generally produced a small increase in burn efficiency, likely due to the thicker slicks created by the higher currents. The increase was more pronounced with ANS, averaging 10%. Increasing the current with Northstar improved the efficiency in calm conditions by an average of 2% but did not improve efficiency in waves.

The presence of waves had a generally negative effect on burn efficiency, as has been noted before in many experiments. Waves reduced the average efficiency between 0.2 and 2% for Northstar, and 8% for ANS.

2.4.2 Aluminum Spheres

Burns with aluminum spheres were conducted with Northstar and ANS crude oils, varying current speed and waves. Two replicates of each test condition were completed. The burn efficiency results are provided in Table 4.

Table 4: Small-scale burn efficiency results (mass percent removed), aluminum spheres.

Current	*Waves*	*Northstar R1*	*Northstar R2*	*ANS R1*	*ANS R2*
Low	No	59	52	42	40
	Yes	57	60	45	37
High	No	57	49	39	31
	Yes	62	62	43	42

Burn efficiency varied between 49 and 62% for Northstar, and 31 and 45% for ANS. In general, the repeatability between replicates was good, varying from 0 to 8%, with an average difference of 5%.

Higher currents resulted in a lower average efficiency (-2.8 to -6.2%) in calm conditions, but a higher average efficiency (1.8 to 3.3%) in waves. The presence of waves had a generally positive effect on burn efficiency, between 2.5 and 7.8%. The exception to this was low current with ANS, where the presence of waves reduced the average efficiency by 0.3%.

The presence of the aluminum spheres generally had a negative effect, compared to the Control burns, reducing the average burn efficiency by between 4 and 15% with Northstar, and 19 and 42% with ANS. The highest reductions in efficiency were noted in the burns in calm conditions.

The aluminum spheres are relatively large (radius of 2.54 cm) compared to the average initial thickness of the test slicks (i.e., 3 to 4 mm) and extended into the water column. We surmise that the high thermal conductivity of the aluminum enhanced the transmission of heat from the oil slicks into the water and cooled the slick faster than in the control burns, leading to early extinction of the burn. Better performance for this concept may be realized by using significantly smaller floating metal or glass spheres (on the order of 2 to 3 mm diameter) that remain entirely within or on top of the oil layer. This would enhance the heat transfer from the fire to the slick, and also provide a surface for wicking, while limiting heat transfer to the underlying water column.

2.4.3 High-Temperature Silicone Sheet

Burns with the high-temperature silicone sheet were conducted with Northstar and ANS crude oils, varying current speed and waves. Two replicates of each test condition were completed. The burn efficiency results are provided in Table 5.

Table 5: Small-scale burn efficiency results (mass percent removed), high-temperature silicone sheet.

Current	*Waves*	*Northstar R1*	*Northstar R2*	*ANS R1*	*ANS R2*
Low	No	71	67	70	73
	Yes	56	50	51	42
High	No	73	69	74	72
	Yes	54	53	46	47

For the first burn conducted with the high-temperature silicone sheet (Northstar R1, with low current and calm conditions), the sheet was mounted on the fire-boom mockup 1 cm below the water surface. After this burn, minor damage to the silicone sheet was noted in two locations: the silicone rubber in two small areas was discolored and was softer than the bulk of the mat. Since it was not envisioned that the silicone mat would be disposable or sacrificial during these tests, the mat was lowered to 3 cm below the water surface to reduce the temperatures it would be exposed to during the remainder of the tests.

Burn efficiency varied between 50 and 73% for Northstar, and 42 and 73% for ANS. In general, the repeatability between replicates was good, varying from 0 to 9%, with an average difference of 4%.

Higher currents had a very small positive effect on the average burn efficiency, ranging from 0.1 to 2.1%, with the higher effect being noted for the burns in calm conditions. The presence of waves had a strong negative effect on the average burn efficiency, ranging from 15.9 to 17.5% with Northstar, and 25.1 to 26.1% with ANS. It was observed that the presence of the silicone sheet in waves disrupted the surface oil slicks, creating areas of open water.

The presence of the silicone sheet generally had a small positive effect in calm conditions, increasing the average burn efficiency between 3 and 4% compared to the control burns. The exception to this was the high current tests with ANS, which had an average burn efficiency 5% lower than the control burns.

The presence of the silicone sheet had a strong negative effect in waves, decreasing the average burn efficiency between 12 and 23% compared to the Control burns. The physical disruption of the surface slick caused by the presence of the solid mat in waves lead to the early extinction of the burns.

2.5 CARBON FIBER MAT

Burns with the carbon fiber mat were conducted with Northstar and ANS crude oils, varying current speed and waves. Three replicates of each test condition were completed. The burn efficiency results are provided in Table 6.

Table 6: Small-scale burn efficiency results (mass percent removed), carbon fiber mat.

Current	*Waves*	*Northstar R1*	*Northstar R2*	*Northstar R3*	*ANS R1*	*ANS R2*	*ANS R3*
Low	No	57	79	66	67	52	66
	Yes	76	62	58	75	61	63

High	No	63	62	78	52	56	66
	Yes	59	59	66	64	65	65

Burn efficiency varied between 57 and 79% for Northstar, and 52 and 75% for ANS. The repeatability between replicates was low, with burn efficiencies from runs under the same conditions varying significantly, up to 22%.

The effect of current was mixed. Increasing current in calm conditions had very little effect on the burn efficiencies measured during the Northstar burns, whereas increasing current in waves had a small negative effect on efficiency of 4%. Increasing current with the ANS burns negatively affected efficiency by between 3.8 and 1.4% in calm conditions and waves, respectively.

The presence of waves had a negative effect on efficiency with the Northstar burns, between 1.9 and 6.4% lower in low and high current, respectively. Conversely with ANS, the presence of waves had a positive effect on efficiency of between 4.4 and 6.9% in low and high current, respectively.

The average burn efficiency relative to the control burns also varied, in some cases being up to 7% more efficient (i.e., ANS in low current and waves), and in other cases being significantly less efficient (i.e., ANS in high current and calm conditions).

As was noted, some of the burns were significantly more efficient than others, as follows:

- Northstar R2 in low current and calm conditions (79% efficiency)
- Northstar R1 in low current and waves (76% efficiency)
- Northstar R3 in high current and calm conditions (78% efficiency)
- ANS R1 in low current and waves (75% efficiency)

These efficiency results are a significant improvement over the control burns for the same conditions and indicate that there is the potential to achieve higher efficiencies under a range of test conditions. Reviewing the video of these tests it was evident that when the carbon mat was on top of the oil layer, with some wrinkles protruding above, that there was a wicking effect that maintained the burn for longer and significantly reduced the amount of residue (Figure 11).

Figure 11: Burn with carbon fiber mat showing wicking at the end of the burn

2.5.1 Additional Tests

Four additional tests were conducted with Northstar crude oil in high currents and calm conditions. The test results are provided in Table 7.

Table 7: Burn efficiency (mass percent removed), additional tests

Concept	*Northstar R1*	*Northstar R2*
Double layer carbon fiber mat	76	-
Metal plate	68	69
Rubber mulch	73	-

The burn efficiency with the double layer of carbon fiber was comparable to the best results obtained with the single layer, and higher than efficiency measured in the control burns (76 compared to an average of 68%). Significant wicking was noted at the end of the burn.

The burn efficiency results with the metal plate were similar to the control burns (average of 68.5 compared to 68%).

The burn efficiency results with the rubber mulch were less than what was achieved during the best runs with the carbon fiber mat, but better than the control burns (73 compared to an average of 68%).

2.6 Small-scale Test Conclusions

The conclusions from the small-scale burn tests are summarized as follows:

- The aluminum spheres had a negative effect on burning efficiency, likely due to transferring heat from the oil layer into the water. Significantly smaller metal or glass spheres (on the order of 2 to 3 mm diameter) that would remain entirely within or above the oil layer may be a superior configuration for this concept.
- The silicone sheet performed satisfactorily in calm conditions but disrupted the oil slick in waves, which negatively impacted the burn efficiency. In calm conditions, maintaining the sheet at a shallower depth than what was used during these tests (i.e., 3 cm) may be advantageous in inducing a vigorous burn phase, but this may result in damage to the silicone sheet from exposure to higher temperatures. An insulating material with a higher thermal tolerance may perform better.
- Tests with the carbon fiber mats were the most variable in burn efficiency results. Some of the replicates showed significantly higher efficiencies than the control burns, while the mats were less effective in other tests at the same current and wave conditions. Review of the test videos determined that when the carbon mat was on top of the oil layer, with some wrinkles protruding above, that there was a wicking effect that maintained the burn for longer and significantly reduced the amount of residue.
- A test with a double layer of carbon fiber produced results comparable to the best results with a single layer of fiber. The double layer of cloth may be helpful in ensuring some of the fabric projects above the slick, to encourage the wicking behaviour.
- A test with rubber mulch resulted in a higher efficiency than the control burns for the same condition. While this material may not be ideal for use during in-situ burning in the field, it serves as an indicator of some desirable properties of a granular product for improving burn efficiency (i.e., oleophilic, thermally insulating, density slightly less than water).

3. Large-scale Burn Tests

Large-scale test burns were conducted at the Cold Regions Research and Engineering Laboratory in Hanover, New Hampshire. The objective of the large-scale test was to evaluate the effects of scale on the performance of the selected interface insulation concepts.

3.1 Apparatus and Materials

The equipment and facilities used to conduct the large-scale tests are described below.

3.1.1 Test Tank

The large-scale tests were conducted in the Geophysical Research Facility (GRF) test basin at CRREL, which measures 60 ft long, 22 ft wide, and 7 ft deep (see Figure 12). Six electric trolling motors were installed at one end of the tank to generate a surface current to hold oil in the boom. Tests were conducted in calm conditions. The salinity of the tank water was measured to be 22.4 parts per thousand, and the temperature was approximately 15°C.

Figure 12: GRF outdoor basin

The trolling motors had the same five speed settings as the motors used in the small-scale tests. Preliminary experiments determined that operating the motors at the maximum speed produced the best oil retention behaviour in the fire-boom. The surface current field was observed to be variable across the tank with significant eddies due to the relatively small size of the tank and the lack of a false floor; however, the current field was sufficient to keep the boom open and in place and hold oil in the boom during burns. Current speed was measured prior to each test in front of the boom opening at three positions across the tank to confirm consistent test conditions, and was found to vary between approximately 0.8 and 1.4 m/s and would also vary with time as eddies and vortices moved.

3.1.2 Test Fire-boom

One full section of Desmi Pyroboom was obtained by CRREL for use during the tests. Relevant specifications for the boom are provided in Table 8, below.

Table 8: Measurements of Desmi Pyroboom

Measurement	*Metric*	*American*
Freeboard	280 mm	11 in.
Draft	480 mm	19 in.
Total Height	760 mm	30 in.
Standard Length	15 m	50 ft.
Mass/Weight	13 kg/m	9 lb/ft
Buoyancy:Weight	3.3:1	3.3:1
Floatation Spacing	860 mm	34 in.

The boom was modified to include a support framework of steel tubing and mesh for the interface insulation materials (Figure 13). The structure was adjustable vertically and was intended to hold the interface insulation material in place in the current during the tests at the desired depth. Figure 14 shows the boom installed in the GRF.

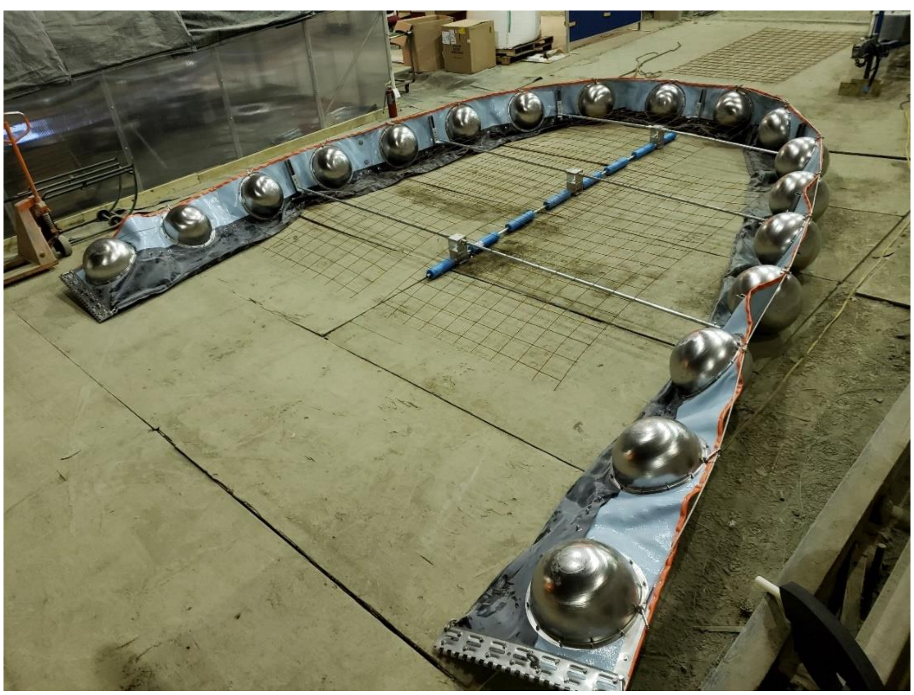

Figure 13: Desmi Pyroboom with attached interface insulation support structure

Figure 14: Fire-boom installed in GRF outdoor basin

3.1.3 Test Oil

Alaska North Slope crude oil was used for the large-scale tests. The test oil was supplied by the Bureau of Safety and Environmental Enforcement in a 1 m^3 container. Oil properties were similar to those presented in Table 1.

3.2 Interface Insulation Materials

Based on the results of the small-scale tests, the most promising insulation concept was the carbon fiber cloth. Several tests with a granular rubber product were also conducted.

3.2.1 Carbon Fiber Mats

Catenary-shaped mats were prepared from three strips of the carbon fiber (5 ft wide by 6.5, 10, and 13 ft long) that were stitched together with a combination of staples and wire (Figure 15). The edges of the mats were trimmed to fit the shape of the section of fire-boom in the tank. Each assembled mat had a surface area of approximately 160 m^2. The mats were weighed prior to being used. One test was conducted with a mat that had been perforated with ~ 5 cm diameter holes in an attempt to improve the permeability of the fabric to oil.

Tests were conducted with the mats being deployed in the boom ahead of the oil, as would typically be expected during a field in-situ burn, as well as with the mat being deployed on top of the oil after it was in the boom. The objective of the latter configuration was to try to maximise the amount of fabric that was present at the oil surface, to encourage wicking.

Figure 15: Carbon fiber mat being installed in boom prior to oil distribution

Tests were conducted to estimate the amount of free water that would cling to a section of carbon fiber after it was used in a burn and removed from the tank, and the free water was decanted. Mats that had been used in a burn and were coated with residue and water were weighed, and then suspended and allowed to dry overnight and then reweighed. The difference in mass was attributed mainly to evaporated water. This data was used to correct the mass of the recovered carbon fiber mats in calculating the mass of oil residue adhered to the mat.

3.2.2 Crumb Rubber

Crumb rubber marketed for use as underlayment for sports fields was obtained for use during the tests. The crumb rubber was applied by hand to the surface of the oil slick. The crumb rubber was applied at a ratio of approximately 10% by weight relative to the oil.

3.3 Large-scale Test Matrix

It was originally planned to complete 8 tests during this phase of the project; however, there was sufficient time and oil to complete 12 tests. The final test matrix is provided in Table 9.

Table 9: Large-scale test matrix.

Test Number	*Oil Volume*	*Interface Insulation*	*Application*
1	40 L	Control	
2	40 L	Carbon Fiber	Before Oil
3	40 L	Carbon Fiber	After Oil
4	40 L	Control	
5	40 L	Carbon Fiber	Before Oil
6	40 L	Crumb Rubber	After Oil

Test Number	*Oil Volume*	*Interface Insulation*	*Application*
7	70 L	Control	
8	70 L	Carbon Fiber	Before Oil
9	40 L	Crumb Rubber	After Oil
10	40 L	Carbon Fiber	After Oil
11	70 L	Carbon Fiber	Before Oil
12	40 L	Perforated Carbon Fiber	After Oil

Two replicates of most test conditions were completed, with the exception of the control burn with 70 L of oil, and the test with perforated carbon fiber sheet applied after the oil was deployed.

3.4 Large-scale Test Procedure

Burns were conducted using either 40 L or 70 L of oil. The required volume of oil was measured into several 20-L plastic pails and weighed prior to being distributed on the tank up-current of the fire-boom (Figure 16). The containers were weighed after the oil was deployed to calculate the initial mass of oil used for each test.

Tests were done with the carbon fiber mats being applied after the oil was deployed, and with the mats being deployed before the oil. Tests were also done with two layers of the carbon fiber. The mats were deployed by hand and loosely attached to the leading edge of the support structure with wire (Figure 17). The crumb rubber was applied by hand (Figure 18).

Figure 16: Deploying oil for the large-scale tests

Figure 17: Carbon fiber mat being deployed in the fire-boom

Figure 18: Applying crumb rubber to oil slick

The test slicks were ignited with a propane torch attached to a long pole (Figure 19). Burn duration was recorded with a stop watch. Figure 20 shows the typical appearance of a test burn.

Figure 19: Ignition of large-scale test burn

Figure 20: Large-scale test burn in progress

After the burn extinguished, the residue was allowed to cool. Carbon fiber mats, if used, were removed from the tank and placed in a large garbage bag, which was then drained of free water and weighed; the initial mass of the mat and an estimate of the amount of free water adhered to the mat were subtracted to determine the mass of residue adhered to the mat.

Crumb rubber residue was collected into a plastic container using a sieve and then weighed. The amount of residue associated with the crumb rubber was calculated by subtracting the mass of rubber applied.

The remaining burn residue was collected using pre-weighed sorbent pads, which were placed into a garbage bag. Free water was drained off, and then the bag of sorbents was weighed. Tests were conducted to estimate the amount of water that would remain adhered to the carbon fiber sheets and sorbent pads after draining the free water. The residue masses were corrected for these amounts.

Burn efficiency was calculated based on the amount of oil removed from the boom during the burn. The mass of oil deployed was measured by weighing the containers before and after pouring the oil into the tank. The mass of residue remaining was measured by weighing the collection materials (i.e., sorbent pads and interface insulation materials) before and after use.

Several small samples of interface insulation materials and burn residue were collected by the Environmental Protection Agency (EPA) after each test. The mass of residue in these samples was measured and included in the burn efficiency calculations.

3.5 Large-scale Test Results and Observations

The results of the large-scale tests are summarized in Table 10. The complete test results are provided in Appendix C.

Table 10: Large-scale test results

Oil Volume	*Insulation*	*Application*	*Burn Efficiency [mass percent]*		*Burn Duration (s)*	
40 L	Control		78	86	169	157
	Carbon Fiber	Before Oil	83	79	380	203
	Carbon Fiber	After Oil	68	67	1838	1119
	Carbon Fiber (Perforated)	After Oil	75		182	
	Crumb Rubber	After Oil	88	89	161	222
70 L	Control		93		182	
	Carbon Fiber	Before Oil	86	88	523	259

The two control burns with 40 L of oil had burn efficiencies of 78 and 86%. This was similar to the efficiency measured for the small-scale control burns with ANS in calm conditions (i.e., 75% and 80% for the two replicates). Burn durations (the time from initial flame to complete extinction) were 169 and 157 s. The control burn with 70 L of oil was more efficient, at 93%, as expected due to the increase in initial slick thickness, with a slightly longer burn duration of 182 s.

When the carbon fiber was applied before the oil, the mat would generally be pushed approximately 5 cm below the surface of the water by the force of the current. Some isolated pockets of fabric would be more buoyant due to air pockets and would be above the surface. The oil when subsequently deployed would generally spread across the entire boom, and appear similar to the control burns. Burn efficiencies were similar to the control burns, at 83% and 79%. The duration of the full burn (100% flame coverage) was similar between the controls and the tests with carbon fiber applied before oil, but there was an extended period at the end of the burns with the carbon fiber where flames would persist at the edges of the boom where some of the fabric was above the oil layer (see Figure 21). It is believed that the fabric in these areas was wicking the oil and extending the burn time; however, the coverage of this area was very small in both burns (< 5%) and the oil consumed during the wicking period was negligible.

Figure 21: Wicking during burn with carbon fiber applied before oil

The tests with carbon fiber applied before 70 L of oil had higher efficiencies than the tests with 40 L of oil, as expected, at 86% and 88%, but these were lower than the 70 L control at 93%. Burn durations were more variable at 523 and 259 s, compared with the control at 182 s; however, some of this variation could have been due to changing ambient conditions such as wind speed and direction.

When the carbon fiber was applied after the oil, it would tend to stay at the surface and not submerge (see Figure 22). These slicks were considerably more difficult to ignite than with the other test conditions. Burn efficiencies were 68% and 67%, which is significantly lower than the control burns. Burn times were considerably longer than the control burns, at between 20 and 30 minutes, with extended periods of wicking after the comparatively short full burn period (6 and 5 minutes, respectively).

It was observed that the carbon fiber fabric is a very tight weave, and not very permeable to the oil. The difficulty to ignite and much lower burn efficiencies indicated that the oil could not easily migrate through the fabric. Better performance may be achievable with this concept with a more permeable fabric. This was the objective with the test with the perforated carbon fiber mat (Figure 23). The perforations did improve the burn efficiency compared with the tests with the regular mat (75%), but this was still less than the control burns (78 and 86%).

Figure 22: Carbon fiber applied after oil, prior to ignition

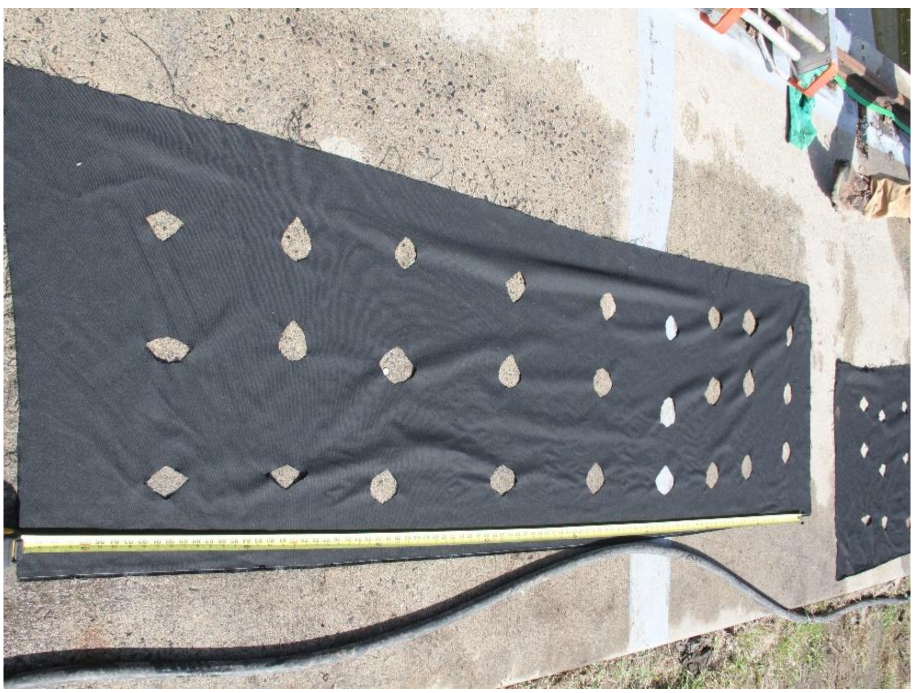

Figure 23: Carbon fiber mat with perforations

The burn efficiencies for the tests with crumb rubber were 88% and 89%, which is a modest improvement over the control burns (78 and 86%). The crumb rubber did not appear to be consumed during the burn; however, the recovered material was softer than when it was first applied.

During the first replicate test, it was observed that the area of the oil slick shrank considerably as the crumb rubber was applied (estimated to be > 30% reduction in area). This did not appear to happen during the second replicate, and no significant difference in performance was evident between the two runs.

3.6 Large-scale Test Conclusions and Recommendations

The conclusions arising from the results of the large-scale tests are as follows:

- The carbon fiber when applied before the oil did not have a significant effect on burn efficiency compared with the control burns. The carbon fiber applied after the oil had a negative effect on burn efficiency. Observations indicated that the oil did not readily migrate through the fabric. It is recommended that future testing of this concept use a more permeable fabric that would allow the oil to penetrate through, and a support structure that would keep the fabric at the surface of the oil layer.
- Crumb rubber had a modest positive effect on the burn efficiency compared with the control tests when applied at a ratio of approximately 10% of the mass of the oil.

4. CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations arising from the study are summarized as follows:

- The large aluminium balls had a negative effect on burn efficiency during the small-scale tests. It is recommended that future testing of this concept focus on smaller particles that would rest entirely within the oil layer. Conductive materials, such as metals, could enhance burning by transmitting more heat from the fire into the slick, while non-conductive materials (such as glass beads or crumb rubber) could serve as a wicking agent or insulating layer.
- It is difficult to situate rigid material such as the silicone sheet at a specific depth (e.g., the interface or surface of the oil slick) in a moving current.
- The carbon fiber when applied before the oil did not have a significant effect on burn efficiency compared to the control burns. The carbon fiber applied after the oil had a negative effect on burn efficiency. Observations indicated that the oil did not readily migrate through the fabric. It is recommended that future testing of this concept use a more permeable fabric that would allow the oil to penetrate through, and a support structure that would keep the fabric at the surface of the oil layer.
- Crumb rubber had a modest positive effect on the burn efficiency compared to the control tests when applied at a ratio of approximately 10% of the mass of the oil. Further testing of this concept could lead to additional improvements in burn efficiency. An alternative product to crumb rubber, with similar density and thermal characteristics, should be investigated.
- A fluid material, such as the aluminum balls and crumb rubber, was easier to deploy and hold in position provided that the material had a density less than water and close to that of oil.

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