

IN SITU BURNING OF ALASKA NORTH SLOPE EMULSIONS

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ABSTRACT: *The onset of water-in-oil emulsion formation in an oil slick often signals the closing of the window of opportunity for in-situ burning as a countermeasure. Water contents in excess of 25 percent in a stable emulsion generally preclude ignition of the slick. A study of in-situ burning of water-in-oil emulsions formed by weathered Alaska North Slope (ANS) crude oil has recently been completed by Alaska Clean Seas. The study consisted of three phases: laboratory-scale burns in Ottawa in a 0.13 m² burn ring, small-scale burns in Prudhoe Bay in 1.2 m² and 3.3 m² pans, and meso-scale burns in a 69 m² circle of 3M Fire Boom in a water-filled pit at Prudhoe Bay. The laboratory-scale tests showed that stable, weathered ANS crude emulsions could be ignited in-situ using conventional gelled fuel igniters only up to a water content of 25 percent. The combination of adding an oilfield emulsion breaker, Petrolite EXO 0894, and the use of gelled crude oil as an alternate igniter fuel, permitted ignition and efficient combustion of weathered ANS emulsions with water contents of 65 percent, the maximum achievable. The small-scale pan tests conducted in Prudhoe Bay proved the same: that normally unignitable emulsions of weathered ANS crude, up to 65 percent water content, could be successfully ignited and efficiently burned outdoors at 0° to 5° C in winds up to 32 km/h with the application of EXO 0894 one hour prior to ignition. Tests with the Helitorch igniter system suspended from a crane showed that a mixture of gelled gasoline and crude oil was the most effective ignition fuel for the emulsions. Attempts were made to ignite emulsion slicks with gelled igniter fuels containing the emulsion breaker; but this technique did not prove as effective as pre-mixing the breaker into the slick. These tests also indicated that the emulsion burns produced a lighter smoke than that from crude oil. Three meso-scale experimental burns were carried out: one involved approximately 13 m³ (80 bbl) of fresh ANS crude as a baseline; one used about 8 m³ (50 bbl) of a stable 50 percent water-in-weathered crude emulsion; and, the final burn was done with 17 m³ (105 bbl) of stable 60 percent water content emulsion. The oil removal efficiency for the fresh crude oil burn was approximately 98 percent. The oil removal efficiencies for the 50 and 60 percent water emulsions were 97 and 96 percent respectively.*

Research on in-situ burning of emulsions has been conducted sporadically over the past 20 years.^{7-9,13-15} In the last few years, the research has intensified and become more focused.^{2,3,6} A brief summary of the state of the art in emulsion burning, condensed from Buist and colleagues⁵ follows.

The ignition and burning of emulsion is similar to burning water-free oil but the processes differ because of the presence of seawater droplets in the emulsion. The existence of the droplets restricts the temperature

of the emulsion to a maximum of 100° C, until the water has been removed. Water can either be removed by boiling or by coalescing and settling the water droplets. Emulsions containing small amounts of water can be burned and the water driven off by boiling. However, the maximum water content that can be removed by boiling is thought to be about 20 to 30 percent. Allen¹ postulated that the water content of the burned portion of the Exxon Valdez slick was in this range. Flame spreading over the slick was reportedly very slow.

Stable emulsions with water contents greater than 20 to 30 percent cannot normally be ignited by conventional methods. It is believed that less stable emulsions with water contents exceeding this range can be burned if powerfully hot igniters are used. Heat from the igniters helps break the emulsion, meaning that the heat enhances water droplet coalescence. The larger water droplets settle through the slick leaving a water-free oil layer on top of the emulsion. Oil in this water-free layer vaporizes and burns just as if it were a pure oil slick. It seems reasonable that this process would continue for as long as the emulsion breaking produces water-free oil at the surface at a rate faster than it is vaporized and burned. If the rate drops, the surface oil slick thins and cools, and the fire dies out. The addition of chemical surfactants called emulsion breakers enhances burning of high water content emulsions by displacing the natural surfactants that stabilize the emulsion water droplets, allowing the droplets to coalesce and settle. Heat transferred into the slick by the combustion process may accelerate the action of emulsion breakers.

One noted feature of burning emulsion slicks is their tendency to die out then flare up again. Two possible explanations for this behavior exist. First, the rate of water-free oil layer production may be less than the rate of oil removal by burning and the burning dies out. However, the breaking of the emulsion continues, which results in an increase in the amount of oil on the slick surface, and, in the presence of a flame, re-ignition of the slick. The other possible cause is the foaming action of the burning slick. The foaming is presumably associated with boiling of water, but its origin and contributing factors are unclear. It is not unusual for a burning emulsion slick to foam over one area of its surface while another is still burning; as the foam breaks, the extinguished surface is re-ignited by adjacent flames.

Minimum ignitable thicknesses for emulsions tend to be greater than for water-free oil slicks (in the range of 5 to 10 mm). As a rule, emulsion slicks burn at a rate proportional to their oil content (that is, an emulsion containing 75 percent water is consumed at a rate of 0.9 mm/min or 25 percent of 3.5 mm/min). Emulsion burning tends to be more vigorous than burning water-free oil slicks due to the boiling of at least a portion of the entrained water droplets. Also, emulsion burning can be more sensitive to wind, presumably because of the more delicate heat balance for emulsion combustion.

Study objective

The objective of the present study was to research the in-situ ignition and burning of emulsions of ANS crude using gelled fuels as igniters and to prove the efficacy of using chemical emulsion breakers as ignition and burn promoters. The objective was met by carrying out three sequential series of tests: indoor laboratory tests in May 1994, burns in small pans in July 1994, and meso-scale burns in a water-filled pit in September 1994.

Laboratory test program

The goals of the initial test program, carried out in Ottawa at the facilities of S. L. Ross Environmental Research, Ltd., were to investigate:

- the burning on water of Alaska North Slope (ANS) crude oil and emulsions;
- the capabilities and limitations of conventional Heli-torch fuels in igniting ANS water-in-oil emulsions;
- the potential of adding emulsion breaking chemicals, or demulsifiers, to the slick prior to ignition to enhance the ignition of ANS water-in-oil emulsions;
- the potential benefits to ignition success of alternate fuels for the Heli-torch; and
- the potential advantages and disadvantages of adding successful emulsion breaking chemicals directly to the Heli-torch fuel.

To conduct the tests with realistic oils and emulsions and determine the effects of evaporation on burning, samples of ANS crude were artificially weathered in the laboratory. This involved bubbling compressed air through three 25 L plastic pails each containing 19 L (initially) of ANS crude. The weathering was stopped in one pail when 10.3 volume percent of the ANS crude had been evaporated; the other two pails were sparged until 27.8 and 27.9 percent of the oil had been evaporated.

Emulsion formation tendency and stability testing. It is known that ANS crude must evaporate to greater than about 15 percent loss by volume in order to form stable emulsions at warm (15° C) temperatures^{4,16} at freezing temperatures indications are that even fresh ANS crude will form stable emulsions.⁴ Standardized emulsion formation tests¹⁸ were conducted with the fresh and 10.3 and 27.9 percent evaporated ANS crude samples. Two series of tests were conducted: one inside a refrigerator at ambient temperatures of 10 to 15° C and another inside an ice-cooled chamber with ambient temperatures of 5 to 8° C. All tests were conducted with 35 ppt (parts per thousand) saline water. The results appear in Table 1. The data clearly illustrate that only the most evaporated oil would form a stable emulsion in the test apparatus.

Emulsion preparation. Several techniques were tried for forming emulsions with the ANS oil. All emulsions were prepared using 35 ppt salt water. The most successful process involved using a gear pump to

mix the emulsion in a 25 L pail placed in an ice-water bath. The oil was added to the pail and a drill-mounted paint mixer was immersed in the oil and started. A 3/4 inch rotary gear pump was then used to recirculate the oil. The salt water was slowly poured into the pail so that it was drawn into the suction of the pump along with the oil. This technique produced fully stable emulsions at room temperature of 60 percent water with the 10.3 and 27.9 percent evaporated oils. It was found that 60 percent emulsions produced with the fresh oil were not fully stable and broke in one to two hours. The maximum stable emulsion using this technique, was about 70 percent water by volume. The reason for the enhanced stability of the emulsions created by the gear pump as compared to the wrist action shaker is probably related to the greater mixing energy imparted by the gear pump.

Chemical emulsion breaker testing. The effectiveness of several commercial chemical emulsion breakers was tested. A modification of a technique for the Burrell wrist-action shaker proposed by Fingas and colleagues¹¹ was used. The procedure involves adding small amounts of emulsion breaker (dose rates ranged from 1:167 to 1:3333 demulsifier to oil) to 65 percent water content emulsion samples floating on salt water in a separatory funnel. The system is shaken for three hours and then stopped. Samples of the oil/emulsion are then taken and analyzed for water content. Three emulsion breakers were tested: Alcopol 0 70% PG, Brexit OEB-9, and Petrolite EXO 0894.

The test emulsions were created with the gear pump using 27.9 percent evaporated ANS crude; the tests were conducted at 6 to 8° C.

The accuracy of these tests is known to be poor,¹⁰ probably not better than ± 20 to 30 percent. In any case, the results indicated that all three chemicals broke the emulsions reasonably well in the test apparatus. Subsequent use of the three chemicals in the burn tests showed that EXO 0894 worked best in breaking the emulsions in a low mixing energy environment.

Burn tests. Tests involving the ignition and burning of oils and emulsions were carried out in a water-filled pan situated beneath a large fume hood. A 40 cm diameter metal burn ring was supported in the center of a 1.2 m diameter pan filled with 32 cm of tap water. Thermocouples were used to monitor water, slick, and flame temperatures during the burns. Each burn involved adding a measured mass (of specified volume) of oil or emulsion to the water surface inside the ring, then igniting it. Preheat time (the time for flame to begin moving away from the igniter), ignition time (the time for the flame to cover the entire slick surface), time to intense burn (when the vigorous burn phase begins), and extinction time (disappearance of the last flame) were noted. Mirrors placed in the bottom of the pan were used to observe the underside of the slick. After each burn the remaining residue was recovered and weighed.

A total of 32 burn tests were conducted. The first 14 burns (Table 2) involved collecting baseline data on the ignition and burning of emulsions of ANS crude as a function of evaporative loss and water content. For these burns, the initial oil/emulsion volume was 2.5 L, equivalent to an initial thickness of 20 mm; as the tests proceeded it became necessary to conserve the 28 percent weathered oil and the initial volume was reduced to 1.9 L (15 mm initial thickness). Previous studies show that this level of reduction in initial thickness will not affect the combustion process, other than to shorten the burn time and reduce overall burn efficiencies.¹⁵ For these baseline runs a progression of ignition sources was used: first ignition was attempted with a 5 cm square sorbent pad (3/16 inch thick) soaked in gasoline, placed on the slick and lit with a propane torch; if this failed to ignite the slick a similar-sized sorbent soaked in fresh ANS crude was used; if this too failed, 100 mL of fresh ANS crude was spread over the surface of the slick and lit with the torch; if the flames died out after about one minute, 200 mL of fresh ANS crude was used; if these flames died out after approximately two minutes, that water content (and all higher ones) for the particular degree of evaporation of the oil were deemed unignitable.

Burn tests 15 through 25 involved experiments, primarily involving high water content emulsions of 28 percent evaporated oil. They investigated the potential improvements afforded by adding emulsion breaker prior to or during ignition. Gelled fuel igniters were used for these runs. For runs involving premixed addition of emulsion breaker, the indicated volume of chemical was added dropwise from a pipette onto the surface of the emulsion slick in the ring and the slick gently stirred with a 2.5 cm wide metal ruler for two to five minutes. A weighed sample of gelled fuel was then ladled onto the slick and lit with a propane torch. For several runs the appropriate amount of emulsion

Table 1. ANS crude oil emulsion formation tendency and stability test results

Test temperature (° C)	Evaporative loss (volume %)	f ₀₁	f ₀₂
Series 1			
10 to 15	0	0	0
10 to 15	10.3	0	0
10 to 15	27.9	1	1
Series 2			
6.4	0	0	0
7.9	10.3	0	0
8.0	27.9	1	1

1. 0 indicates no tendency to form an emulsion; 1 indicates a strong tendency.

2. 0 indicates a highly unstable emulsion; 1 indicates a highly stable emulsion.¹⁸

Table 2. Laboratory-scale burn test results

Exp. No.	Evap. (%)	Water (%)	Emulsion mass (g)	Oil Vol (mL)	Residue mass (g)	Ignition #	Ignition type	Ignition time	Extinction time	Breaker type	Breaker amnt.	Mass Oil burned (g)	Burn Rate (mm oil/min)	Burn efficiency (%)
1	0	0	2187.5	2500	236.74	1	gas pad	00:00:00	00:12:23	none		1950.76	1.43	89.18
2	10.3	0	2241.0	2500	137.20	1	gas pad	00:00:05	00:17:03	none		2103.80	1.10	93.88
3	28	0	2405.0	2500	596.00	1	gas pad			none				
						2	oil pad			none				
						3	100 mL oil	00:00:00	00:22:05	none		1809.00	0.70	75.22
4	0	12.5	2420.0	2500	579.50	1	gas pad	00:00:07	00:12:53	none		1538.00	1.10	72.63
5	0	25	2243.4	2500	167.20	1	gas pad	00:00:20	00:11:08	none		1515.35	1.28	90.06
6	0	40	2432.3	2500	167.20	1	gas pad	00:02:17	00:09:40	none		1292.18	1.59	88.54
7	0	60	2448.8	2500	175.10	1	gas pad	00:05:59	00:11:09	none		804.42	1.42	82.12
8	10.3	12.5	2270.4	2500	947.80	1	gas pad	00:00:15	00:13:30	none		1038.80	0.70	52.29
9	10.3	25	2332.1	2500	566.00	1	gas pad	00:00:15	00:11:15	none		1183.08	0.96	67.64
9a	10.3	25	566.0		140.50	2	gas pad			none		425.50	0.59	75.18
						3	oil pad			none				
						4	100 mL oil	00:00:00	00:06:26	none		1608.58		91.97
10	10.3	40	2430.1	2500	532.70	1	gas pad	00:04:54	00:16:47	none		925.36	0.69	63.47
11	10.3	60	2529.0	2500	207.50	1	gas pad		00:03:34					
						2	oil pad	00:06:22	00:13:06	none		804.10	1.06	79.49
12	28	12.5	1803.8	1900	801.20	1	gas pad		00:01:34	none				
						2	oil pad		00:00:59	none				
						3	100 mL oil	00:00:17	00:12:15	none		777.12	0.56	49.24
13	28	25	1771.6	1900	741.80	1	gas pad		00:01:44	none				
						2	oil pad		00:00:41	none				
						3	100 mL oil	00:00:22	00:01:24	none				
						4	200 mL oil	00:00:18	00:17:59	none				
												586.90	0.29	44.17
14	28	40	1857.3	1900	622.90	1	gas pad		00:02:18	none				
						2	oil pad		00:01:16	none				
						3	100 mL oil	00:00:29	00:01:08	none				
						4	200 mL oil	00:00:11	00:02:17	none				
14a	28	40				5	gas pad		00:00:47	Brexit	1:500 (d:e)			
						6	oil pad		00:01:43	none				
						7	100 mL oil	00:00:24	00:20:19	none		491.48	0.21	44.10
15	28	40	1825.7	1900	493.00	1	31.4 g napalm		00:01:17					
						2	28.8 g napalm		00:01:20	EXO-894	4 mL (pure)			
16	28	40	1783.6	1900	317.60	3	100 mL crude	00:00:29	00:10:13			602.42	0.53	54.99
						1	31 g gelled diesel		00:01:04					
						2	33.8 g gelled diesel		00:00:57	Alcopol	4 mL			
						3	100 mL crude	00:00:41	00:03:18					
						4	100 mL crude	00:00:52	00:14:36			752.56	0.47	70.32
17	28	40	1787.2	1900	236.20	1	31.74 g gelled crude		00:00:36					
						2	30.03 g gelled crude		00:00:43	EXO-894	4 mL			
						3	61.1 g gelled crude		00:01:16					
						4	100 mL fresh ANS	00:01:06	00:12:39					
						5	100 mL fresh ANS	00:00:18	00:03:14			836.12	0.62	77.97
18	28	50	1812.7	1900	187.60	1	31 g gelled crude		00:00:51	EXO-894	4 mL			
						2	85 g gelled crude	00:01:31	00:10:19			718.75	0.70	79.30
19	28	50	1809.6	1900	140.00	1	79.4 g napalm		00:01:13	EXO-894	4 mL			
						2	85.8 g gelled crude	00:01:38	00:03:54					
						3	86.64 g gelled crude	00:00:55	00:10:09			764.80	0.71	84.53
20	28	50	1808.8	1900	189.90	1	100 mL gelled crude		00:02:33	EXO-894	4 mL			
						2	85.6 g gelled crude		00:03:36					
						3	90.58 g gelled crude	00:01:33	00:09:15			714.50	0.80	79.00
21	28	60	1826.6	1900	194.40	1	70 g gelled diesel	00:01:08	00:07:27	EXO-894	4 mL	536.24	0.73	73.39
22	28	60	1457.0	1500	105.78	1	81 g gelled diesel/gas		00:01:32	EXO-894	4 mL			
						2	83 g gelled diesel	00:01:07	00:05:50			477.02	0.87	81.85
23	28	60	2463.7	2500	133.35	1	100 mL napalm		00:01:11	EXO-894	1:2000 (d:o)			
						2	81 g napalm		00:01:46	EXO-894	1:1000 (d:o)			
						3	83.9 g napalm	00:00:36	00:07:49	EXO-894	1:500 (d:o)	852.13	1.02	86.47
24	10.3	60	2444.7	2500	114.90	1	100 mL gelled diesel/gas	00:00:24	00:08:53	EXO-894	4 mL	862.98	0.90	88.25
25	10.3	70	2507.4	2500	128.00	1	100 mL napalm	00:01:03	00:02:16					
						2	80 g gelled diesel/gas	00:00:53	00:06:58	EXO-894	4 mL	624.22	0.91	82.98
26	0	40	2387.3	2500	350.90	1	75.5 g napalm	00:00:45	00:02:08	None				
						2	67.2 g napalm	00:00:32	00:12:15	EXO-894	2 mL	1081.48	0.84	75.50
27	0	60	2453.7	2500	150.10	1	82.5 g gelled diesel/gas	00:01:01	00:09:54	EXO-894	4 mL	831.38	0.85	84.71

breaker chemical was added to the gelled fuel igniter during the gelling process; if the treated igniter failed to result in successful, effective combustion, the residue remaining was gently stirred for five minutes and ignition attempted again with an untreated gelled fuel igniter.

The results given in Table 2 can be summarized as follows:

- With fresh ANS crude, even emulsions containing 60 percent

water (the maximum stable water content was less than 67 percent for fresh ANS crude) could be ignited and burned with high oil removal rates and efficiencies. This presumably relates to the lower stability of fresh ANS emulsions.

- With 10 percent evaporated ANS crude, the strength of ignition source required to achieve effective burning increased with in-

creasing water content, but a 60 percent water-in-oil emulsion could still be ignited, although the burn rates and efficiencies were lower than with fresh ANS and the combustion at higher water contents was visibly weaker. A higher oil removal efficiency was achieved in one test (No. 9 with 25 percent water) by allowing the initial residue to cool and lose water and then re-igniting it. The above-noted behaviors are probably related to the slightly higher stability of 10 percent evaporated ANS crude emulsions.

- The maximum burnable water content for the 28 percent evaporated ANS crude was approximately 25 percent by volume. It required 200 mL of fresh crude to ignite this emulsion and the combustion was very weak.
- Of the three emulsion breakers tested in the premixed mode (4 mL added dropwise to a 28 percent evaporated, 40 percent water emulsion—1:285 demulsifier to oil ratio), EXO 0894 produced the best results: the highest burn efficiency after one ignition, the highest burn rate, and the strongest, most stable flames.
- The application of 4 mL of EXO 0894 allowed ignition and efficient, strong burning of 60 percent water content emulsions of 28 percent evaporated ANS crude (the maximum water content tested) and, 70 percent water content emulsion of 10 percent evaporated ANS crude.
- Premixed addition of EXO 0894 to the slick was the most effective delivery method. Gentle mixing for a few minutes was necessary to get the maximum benefit from the chemical; a time delay was necessary between chemical application and ignition to allow the emulsion breaking process to begin.
- The minimum dosage of premixed EXO 0894 required to ignite a 60 percent water content emulsion of 28 percent evaporated ANS crude was 1:500 demulsifier to oil.
- Addition of 4 mL of EXO 0894 into the gelled fuel igniter during the gelling process enhanced the emulsion breaking performance of the igniter, but not as much as premixing of the demulsifier. It was noted that if a treated fuel igniter failed to ignite the test slick, gentle mixing of the igniter residue for five minutes followed by re-ignition of the slick with an untreated igniter produced results as good as if the emulsion breaker chemical had been premixed.
- Some of the emulsion breaker remained with the burn residue; this was evidenced by the appearance of holes in the residue created by the chemical's herding action.

Igniter recipes. In a second series of burns in the laboratory a variety of gelled fuel igniters were created and their ignition properties investigated. Four base fuels were used to create the igniters: unleaded gasoline, automotive diesel, a 50/50 mix of gasoline and diesel, and fresh ANS crude.

The concentration of Surefire gelling agent (available from Simplex Mfg., the producer of the Heli-torch) used to produce gelled fuel at cool temperatures is suggested to be 17.5 g/L.¹⁷ This concentration produced an appropriate product when using gasoline; however, when using mixtures of gasoline and diesel as the fuel, the gel time became longer and the viscosity of the resulting product and its viscoelasticity (a measure of its cohesiveness) appeared to decline as the fuel became heavier. It was difficult to produce a gelled fuel with fresh ANS crude, but dosages of 30 g/L of Surefire resulted in a somewhat gelled product, but visibly much less viscous than the gelled refined fuels.

The addition of surfactant to the fuel during the gelling process reduced the effectiveness of the Surefire. The chemical emulsion breaker EXO 0894 was added to the fuel first at the concentration of 40 mL/L, then 17.5 g/L of Surefire was added and mixed. The concentration of EXO 0894 in the gelled fuel was based on delivering 4 mL of chemical in a 100 mL blob of gelled fuel. The resultant refined fuel gels took longer to set and appeared to be less viscous and viscoelastic than the gels not treated with EXO 0894. The addition of EXO 0894 to fresh ANS crude appeared to render it nearly ungellable even with 35 g/L of Surefire gelling agent.

Temperatures (both flame and beneath the igniter) were measured for the gelled igniters of gasoline, 50/50 gas/diesel, diesel, and crude with EXO 0894. The 250 mL samples of each fuel were placed on the water surface inside the ring and then lit with a propane torch.

The gasoline (napalm) igniter, when first ignited, produced a high flame (1.5 m) that declined over about one minute to 0.5 m. Peak flame temperatures occurred initially and achieved temperatures of 700 to 800° C. After one minute the flame temperatures had declined and steadied to about 400 to 600° C.

The gelled 50/50 gasoline/diesel igniter initially produced a flame 1

Table 3. Igniter burn times and subsurface temperatures in laboratory tests

	Gelled gas	50/50 Gas/Diesel	Diesel	ANS crude
Initial avg. water temperature (° C)	21	22	23	24
Max. temperature in undersurface of igniter (° C)	72	111	127	152
Max. temperature 5 mm below igniter (° C)	42	62	72	63
Max. temperature 15 mm below igniter (° C)	28	29	34	38
Burn times (min:sec)				
full ring diameter	0:30	1:10	1:00	2:23
total	2:17	2:14	2:27	2:47

m high which declined to 0.5 m after about one minute. The maximum flame temperatures achieved were about the same as for the gelled gasoline (700 to 800° C) but these flame temperatures were sustained over a longer period (2 min vs 1 min for the gelled gasoline).

The gelled diesel igniter was more difficult to light with the propane torch than the previous two. Initial flame heights reached only 0.5 m. Although a maximum flame temperature of almost 800° C was achieved with this igniter, the average flame temperatures were lower than for the previous two.

The treated gelled crude igniter was easier to light with the propane torch than the gelled diesel. It generated flames of 0.5 to 0.75 m high; and a maximum flame temperature of about 800° C was achieved. Near the end of the burn the center of the igniter extinguished but the edges continued to burn.

Table 3 compares the temperatures measured beneath the various igniters and their burn times. These results indicate that the crude oil igniter transferred the most heat into the water beneath it; however, the igniters incorporating gasoline generated higher initial flames (and thus better radiant heating). It appeared that the 50/50 gelled gas/diesel igniter was the best compromise, offering higher initial radiation to its surroundings, a sustained burn of reasonable duration, and moderate heat transfer rates to underlying fluids.

Outdoor burn tests in pans

A series of small-scale test burns were undertaken in Prudhoe Bay, Alaska, in July 1994. They were designed to:

- test the efficacy of alternate gelled fuel mixtures in a Heli-torch;
- determine the maximum ignitable water content of weathered ANS crude oil emulsions outdoors in Arctic summer conditions;
- determine the efficacy of chemical emulsion breaker addition to enhance ANS crude emulsion ignition and burning on water;
- determine the best method of applying the emulsion breaker to the slick for ignition; and
- determine the minimum fire size required to establish burning of an emulsion slick.

A combination of air sparging, recirculation with a pump, and spraying the oil through a nozzle was used to weather 0.8 m³ of fresh ANS crude in an outdoor tank. Over a two-week period the oil lost 23.8 percent of its volume to evaporation.

Emulsions were prepared for these tests by recirculating a measured volume of the weathered ANS crude through a two-inch gear pump and drawing the appropriate volume of sea water into the pump suction through a valved tee. The flow rate of sea water was maintained at one sixth the recirculation rate of the pump, as prescribed by Gåseidnes.¹² The recirculation was continued for 10 minutes after the last water was added. The water droplets in the emulsions were examined under a microscope; the majority were less than 10 µm in size the average was probably less than 1 µm. Samples of the emulsions did not break at 10°

C over 72 hours. One sample was still unchanged after approximately 60 days in a refrigerator.

Igniter drop tests. A series of tests were carried out with 7.6 L batches of various gelled fuel mixtures dropped from a Heli-torch suspended 3 to 6 m above a water-filled, 1.2 m² square burn pan. Different ratios of gelling agent, gasoline, diesel, fresh crude oil, and EXO 0894 were experimented with. The best mixture, from the perspectives of ease of production, consistency, delivery by the Heli-torch, and ignition power was concluded to be a 50/50 mix of gasoline and crude oil gelled (at 10° C) with 45 g/L of Surefire. The addition of EXO 0894 rendered the fuels more difficult to gel and reduced their shelf life to less than 12 hours. Drop tests indicated that the diesel, diesel/crude, and crude mixtures could not easily be ignited by the static Heli-torch in the prevailing winds of 8 to 16 km/h. A significant fraction of gasoline was needed in the fuel for ignition by the Heli-torch.

Pan burn test results. Two sizes of square pans filled with fresh water were used for these tests: a 1.2 m² pan and a 3.3 m² pan. For most of the tests, 400 to 500 mL of gelled igniter fuel were placed in baggies, or ladled, evenly spaced over the area of the emulsion slick. The Heli-torch was not used due to the difficulty of delivering small, measured amounts of fuel accurately over a very small slick area. The results of the pan burns are given in Table 4. Runs 1 and 2 were conducted to identify the maximum ignitable water content of emulsions of the 23.8 percent evaporated ANS crude. The water temperature for these initial runs was 20° C. The results showed that, even with the 50/50 gasoline/crude oil igniter, a 25 percent water emulsion could not be ignited. Application of EXO 0894 to the same slick resulted in a strong burn and a 95 percent removal efficiency. Subsequent tests in the 1.2 m² pan (runs 3, 4, 5, and 6) showed that the dropwise application of EXO 0894 followed by 10-min mixing with a 5 cm wide stick followed by a one hour waiting period was necessary for successful ignition and

Table 4. Small-scale pan burn test results

Run No.	Water (%)	Emulsion		Pan size (m ²)	Wind 2 m (km/h)	Fuel No.	Ignition No.	Ignition time	Extinction time	Residue (kg)	Mass oil burned (kg)	Burn rate (mm oil/min)	Burn efficiency (%)
		Volume (L)	Mass (kg)										
1	12.5	15.1	13.6	1.2	10-13	g/g	1	2:33	8:39	0.815	11.1	1.74	93.17
2	25	17.7	16.3	1.2	10	g/g	1		1:30				
						g/d	2		3:25				
						g/c	3		3:21				
3	40	22.1	20.0	1.2	13-14	g/c	4	4:20	9:36	0.645	11.6	2.09	94.72
					13-14	g/c	1		2:07				
					13-16	g/c	2		2:59				
4	40	22.1	19.1	1.2	13	g/c	3	0:30	8:33	0.455	11.5	1.36	96.20
						*	1		5:04				
					14-16	4/500 mL							
5	50	26.5	21.8	1.2	16+	g/c	2	0:15	6:39	0.486	11.0	1.63	95.76
						g/c	1		2:13				
					29-34	4/500 mL							
						g/c	2	0:39	5:20	0.455	10.4	2.12	95.83
6	60	33.1	31.6	1.2	30-34	4/500 mL							
						g/c	1	0:20	8:02	0.455	12.2	1.50	96.39
7	40	22.1	20.7	1.2	27	4/500 mL							
						g/c	1		1:42				
					34	4/500 mL							
						g/c	2	0:50	3:33	3.24	9.2	1.20	73.96
						4/500 mL							
					18.9 L	fuel	3			n/m			
8	25	88.2	81.8	3.3	30-34	g/c	1	1:00	14:26	14.18	47.2	1.22	76.89
						4/500 mL							
					29	g/c	2		5:37	4.28	9.9	0.66	69.82
						4/500 mL							
Total											57.1		93.03
9	40	110.5	103.2	3.3	39-51	g/c	1		3:36				
					35-38	g/c	2	1:30	5:49				
					26	4/500 mL							
						g/c	3		2:53				
						3 L							
						50/50							
10	60	165.8	160.5	3.3	8-10	g/c	4	0:20		14.38	47.5	0.91	76.77
						10/400 mL	1		1:38				
					11	g/c	2	0:00	11:22	1.28	62.9	1.92	98.01
						16/500 mL							
11	65	37.9	36.7 (calculated)	1.2	5-8	g/c	1	0:30	9:13	0.42	12.4	1.22	96.73
						4/500 mL							

Legend: g/c = gas + crude
 g/g = gas + gas
 g/d = gas + diesel
 4/500 = 4 igniters, 500 mL each
 n/m = not measured

efficient burning. Run 7 attempted to add the emulsion breaker to the slick by mixing the chemical into the gelled fuel. The results of the initial ignition attempts (a 74 percent oil removal efficiency only after stirring following the first ignition failure) led to the withdrawal of this technique from further testing. It is possible that for other oil/emulsion breaker combinations this approach may hold promise.

The tests in the 3.3 m² pan (runs 8, 9, and 10) confirmed the results of the smaller pan burns. In run 8, the residue remaining after the first burn died out (with 76.9 percent removal) was re-ignited. This resulted in a 93 percent overall removal efficiency. At the end of this burn, the residue sank to the bottom of the pan as it cooled. Run 9 showed that emulsions could not be ignited in winds of 35 km/h (9.7 m/s), which is in agreement with Bech, Buist, and then co-workers.^{3,5} The emulsion from this test was left overnight and successfully re-ignited the next morning (with a water temperature of 3° C) even though the emulsion had gelled to a semisolid mat overnight. For run 10, only the upwind half of the 60 percent water content slick had gelled fuel igniters placed on it. The flames from the first ignition did not spread downwind to engulf the entire slick area. A subsequent ignition with a larger number of igniters spread over the entire slick resulted in a successful burn. It appears that the minimum fire size for ignition of high water content emulsions is greater than that required for water-free crude (at about 1 m²), and is greater than 3.3 m². The final test, in the 1.2 m² pan, resulted in successful ignition of a 65 percent water content emulsion.

One interesting observation during these burns was that the flames from high water content emulsions were more luminous than those from water-free crude burns, and the smoke was much lighter. This may be due to the combination of the reduced oil combustion rate of emulsions allowing more air to mix with the fuel vapors during the combustion process, and the presence of water vapor in the combustion zone.

Meso-scale tests

The meso-scale test burns were designed to:

- test the effectiveness of gelled gasoline/crude oil igniters in a Heli-torch flown beneath a helicopter,
- examine ignition and flame spreading over large emulsion slicks treated with emulsion breakers, and
- determine the effects of increased scale on emulsion burning processes, rates, and efficiencies.

The tests were conducted in a 28 m × 20 m × 1 m deep, lined pit filled with fresh water. A 30 m long section of 3M Fire Boom was formed into a circle in the center of the pit. The boom encompassed an area of approximately 69 m². An initial volume of 13.2 m³ of fresh ANS crude was evaporated to 17.4 percent loss over a two-week period using air sparging, recirculating, spraying, and, in the final stages, steam heating. The emulsions were created using a 48 m³ vacuum truck equipped with a 3 inch gear pump plumbed with a valved tee for seawater injection on the suction side. The required volume of oil was drawn into the truck and recirculated, then the required volume of sea water was drawn into the pump through the tee at one sixth the estimated recirculation rate. Mixing continued for two hours after adding all the sea water. The emulsion was mixed periodically afterward and just prior to being added to the slick. A sample of the 50 percent water emulsion was completely stable for 72 hours at ambient temperatures; a sample of the 60 percent water emulsion had been stable for 24 hours prior to shipment to the laboratory for analysis. At the time of writing the emulsion analysis had not been completed.

One burn test was conducted with fresh crude oil as a baseline, both for this study and for the purposes of sampling the smoke plume. This smoke particulate monitoring program was conducted by a team of 12 scientists from NIST, NOAA, and EPA; the results of their sampling will be reported separately.

Prior to each burn, the vacuum truck was weighed at a scale then backed up to the pit to discharge the oil or emulsion for the test. For the first offloading the truck was on an incline and not all the emulsion load was discharged. The emulsion remaining in the truck was incorporated into the emulsion produced for the last burn. Also, the truck containing the 50 percent water emulsion from the first burn was left outside overnight and proved almost impossible to pump at the near-freezing temperatures. The 60 percent emulsion was made with warmed oil and

cold sea water, then the truck was parked in a building overnight. Its temperature was 7° C in the boom prior to ignition.

With the emulsion in place, 26.5 L of EXO 0894 was sprayed on the surface of the slick from pressurized garden-type sprayers. For the 50 percent water emulsion burn the chemical and sprayers had been left outside overnight and the emulsion breaker had become very viscous and difficult to pump. For the 60 percent emulsion burn the chemical and sprayers were kept in a warm location until the last moment; this greatly improved the application of the breaker.

After the emulsion breaker had been applied to the slick, it was mixed using paddles from the edge of the fire boom and from a man-basket suspended over the middle of the slick. This mixing was continued for 30 minutes. For the 50 percent water emulsion burn, the mixing was gentle and involved primarily the surface layer of the slick; for the 60 percent water emulsion, the mixing was much more vigorous and care was taken to mix the entire depth of the slick.

The gelled fuel prepared for the emulsion burns was a mixture of 75 percent gasoline and 25 percent fresh crude oil; the 50/50 mixture had proven difficult to ignite as it exited the Heli-torch under a helicopter during dry-run tests. This had not been encountered during the pan burn tests in July. For each emulsion burn a 38 L batch of the 75/25 mixture was prepared in a pail using a Surefire dosage of 30 g/L. For the 50 percent water emulsion test the 38 L batch was loaded into a 205 L Heli-torch and flown underneath an MBB 105 helicopter. The helicopter hovered with the Heli-torch suspended approximately 10 m above the slick and released the entire load in about 40 seconds. The gelled fuel was spread over the entire area of the slick. For the fresh crude burn, the Heli-torch was loaded with gelled gasoline and flown at approximately 5 m/s over the upwind edge of the slick releasing balls of burning fuel. The weather precluded flying operations for the 60 percent water emulsion test and the 38 L batch of gelled 75/25 fuel was poured from a man-basket in six separate patches on the surface of the slick. Six hand-held igniters were used to light the gelled fuel patches.

Meso-scale burn results. At the time of writing not all the data sources had been processed (for example, videotapes and weather station reports). The available results of the meso-scale burns are summarized in Table 5. When the burning 75/25 gelled crude was dropped onto the 50 percent emulsion it quickly engulfed the entire surface of the slick. The burn proceeded steadily for approximately eight minutes then the fire died back until it was burning only behind the leeward side of the upwind portion of the fire boom. A considerable amount of white vapor emanated from the slick at this time. After about a minute the flames spread back out over the entire slick surface and steady burning resumed. This dying-out and flaring-up phenomenon, denoted as pulsing, occurred about 10 times during the first half of the burn; in the second half of the burn the phenomenon did not occur. This behavior was not observed during the fresh crude or 60 percent emulsion burns.

Table 5. Meso-scale burn preliminary data summary

	Burn 1	Burn 2	Burn 3
Date	9/8/94	9/10/94	9/11/94
Temperature (°C)	-2.5	-2.5	0.5
Wind speed (km/h)	28.0	22.0	11.0
Volume of emulsion (m ³)	7.7	12.2	16.6
Volume of oil (m ³)	3.9	12.2	6.7
Percent oil	50	100	40
Degree of oil evaporation (% vol)	17.4	0	17.4
Volume of water (m ³)	4.0	0	10.0
Percent water	50	0	60
Volume of EXO 0894 (L)	26.5	0	26.5
Ignition time (min)	<1	<1	3
Extinguishment time (min:sec)	55:34	43:42	47:22
Estimated oil burn rate (mm/min)	1	4	2
Weight of slick (kg)	7,536	10,827	16,364
Weight of oil in slick (kg)	3,768	10,827	6,545
Weight of burn residue (kg)	103	170	212
Oil removal efficiency (%)	97.3	98.4	96.7

1. Based on area enclosed by boom only; not including burning oil outside of boom

There are several possible causes for this pulsing. One could have been the slow release of oil from the emulsion (due to poor emulsion breaker mixing or action) that allowed the combustion process to consume oil faster than it could be released from the emulsion. Another could have been the wind speed during the test. The 28 km/h winds were near the 35 km/h blow-out velocity noted during the pan-scale tests. Other causes for the pulsing behavior could be related to slick thickness or temperature.

Approximately five minutes after the ignition of the 50 percent emulsion some oil escaped from the boom. This failure continued throughout the remainder of the burn, occasionally resulting in a ring of fire around the outside perimeter of the boom and fires against the downwind edge of the pit as oil accumulated.

After 52 minutes, the fire began to die out and only oil herded against the downwind edge of the fire boom was burning. No vigorous burn phase was observed although the fire could be heard hissing throughout. The burn lasted for a total of 55 minutes and 34 seconds and consumed 97.3 percent of the 3,770 kg of oil in the emulsion placed in the boom. The characteristic holes in the residue, indicative of the presence of the emulsion breaker in the residue, were observed. The preliminary estimate of the burn rate (using only the slick area inside the boom) was 1 mm/min. This low rate reflects the pulsing phenomenon during the first half of the burn. As the residue in the boom cooled, it sank; this residue was recovered from the bottom of the pit. It was a solid similar to peanut brittle. Samples of the residue have been sent for analysis.

The fresh crude oil burn ignited quickly and easily using the gelled gasoline. Again some oil began to escape from the boom about five minutes after ignition. This oil ignited and increased the burn area by 2 to 3 m around the perimeter of the boom. The area between the downwind edge of the boom and the adjacent pit wall also was covered with burning oil. About 30 minutes after ignition, the fire area reduced to only the area inside the fire boom. No pulsing behavior was observed during this test. After approximately 33 minutes, the fire began to die down; and for the next 10 minutes, burned only on the downwind side as residue was herded there by the wind. Interestingly, no vigorous burn phase was noted. The fire went out after a total of 43 minutes 42 seconds. The residue slowly sank as it cooled; it was subsequently recovered and was in the form of a brittle solid. The oil removal efficiency for this burn was 98.4 percent. The initial estimate of the burn rate was 4 mm/min. This result is probably high due to the considerable amount of burning was taking place outside the area enclosed by the boom.

The ignition of the 60 percent water emulsion using 38 L of 75/25 gasoline/crude gel and six hand-held igniters was successful; but downwind and crosswind flame spreading was slower. Unlike the first two burns, it took about three minutes for flames to engulf the entire slick. Leakage of oil from the boom occurred again, with flames extending 2 to 3 m outside the downwind perimeter of the boom. No pulsing was noted with this emulsion; but the flame was visually much more luminous than the fresh crude burn (as was the flame from the 50 percent water content emulsion burn). After 42 minutes of steady burning, the fire began to die; again no obvious vigorous burn phase was noted, although the fire seemed to be radiating more heat in the latter stages and could be heard hissing throughout. The characteristic holes in the residue were observed. The fire continued to burn in an ever-shrinking area of the downwind portion of the fire boom and against the downwind edge of the pit. The residue inside the boom sank once the fire went out after a total burn time of 47 minutes 22 seconds. The oil removal efficiency was 96.7 percent by mass. The initial estimate of overall burn rate was 2 mm/min.

Visually comparing the smoke from the three burns, the emulsion burns tended to produce a lighter, grey-colored smoke compared to the heavier, black smoke produced by the fresh crude burns.

Conclusions

The following preliminary conclusions were drawn from the study.

- The maximum ignitable water content for weathered ANS crude emulsions was 25 percent or less using conventional techniques.
- The process of adding EXO 0894, mixing it into the slick, and then waiting one hour permitted ignition and consistently efficient

burning of 25 to 65 percent water content, stable emulsions of weathered ANS crude.

- The combination of gasoline and crude oil as gelled fuel for the Heli-torch resulted in an effective igniter for weathered ANS crude emulsions.

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