

**IN-SITU BURNING OF ALASKAN OILS AND EMULSIONS:
PRELIMINARY RESULTS OF LABORATORY TESTS WITH AND
WITHOUT WAVES**

I. Buist, J. McCourt, K. Karunakaran, C. Gierer
S.L. Ross Environmental Research Ltd.
D. Comins, N. Glover
Alaska Clean Seas
and
B. McKenzie
Alyeska Pipeline Services Company

Abstract

A study of the efficacy of in-situ burning (ISB) as a response tool for oils transported in Alaska is being undertaken. The first phase of the work involved small-scale laboratory burn tests to determine the limits to ignition of slicks of four oils (Drift River crude, Endicott crude, Pt. McIntyre crude and IF-30 fuel oil) imposed by evaporation and emulsification. Tests were also conducted to determine the effectiveness of chemical emulsion breakers in extending the ignition limits. The preliminary results indicate that the combination of evaporation and emulsification can severely curtail ignition of slicks of the four oils, but that the application of an emulsion breaker can significantly extend the window of opportunity for ISB. Both the limits to ignition and the effectiveness of emulsion breaker addition were found to be oil type dependent; oil-specific testing is required to ascertain the potential effectiveness of ISB and emulsion breaker addition.

This paper also presents the preliminary results of a series of small scale laboratory burn tests with Alaska North Slope crude in waves. Waves had an effect on the burning of fresh, weathered and emulsified slicks. Burn efficiency and burn time both decreased with increasing wave steepness (used as a measure of wave energy). Burn rate and the amount of residue increased with increasing wave steepness. The effect was most pronounced for the heavily weathered oil and emulsions.

INTRODUCTION

*In-situ burning (ISB) of oil spills on water has the potential to quickly remove large quantities of oil from the water surface and can be an effective countermeasure during a spill cleanup; however, evaporation of an oil's light ends and water-in-oil emulsion formation can quickly lead to the slick becoming unignitable and the closing of the "window-of-opportunity" for a successful *in-situ* burn. Recent tests in Alaska, which followed from studies in Norway and Canada, have demonstrated the potential for greatly extending the ISB window-of-opportunity by applying chemical breakers to emulsions contained in fire resistant booms. Previous laboratory tests, small-scale burns in pans, and meso-scale tests have proven that the addition of emulsion breaking chemicals to certain oils can permit the successful ignition and burning of otherwise unignitable slicks.*

Environment Canada. Arctic and Marine Oilspill Program (AMOP) Technical Seminar, 19th. Volume 2. Proceedings. June 12-14, 1996, Alberta, Canada, Environment Canada, Ottawa, Ontario, 1033-1061 pp, 1996.

IN-SITU BURNING OF WATER-IN-OIL EMULSIONS

Two basic processes are involved in the burning of emulsified oils (S.L. Ross 1995, Guenette et al. 1994 and 1995). The first is the vaporization of the water droplets in the emulsion or the "breaking" of the emulsion, that is its separation into oil and water phases. These form a layer of water-free oil floating on top of the slick. The second process involves the combustion of this water-free oil layer. Rate controlling processes likely include the rate of emulsion breaking, the rate of vaporization of emulsion water and the rate of heat transfer through the emulsified slick. It has been postulated (S.L. Ross 1995, Guenette et al. 1994) that it is the removal of water which controls emulsion burning. If *in-situ* burning of emulsions is to be self-sustaining, the rate of generation of water-free oil must be equal to or greater than the rate of combustion of the free oil.

The concept of applying emulsion breakers to a slick to promote ignition of emulsified oil slicks has been successfully demonstrated in a number of recent studies (S.L. Ross 1995, Guenette et al. 1994 and 1995). In particular, a previous study (S.L. Ross 1995) showed that the commercial emulsion breaker EXO 0894 significantly extended the limits to ignition and efficient large-scale burning for emulsions of weathered Alaska North Slope (ANS) crude in quiescent conditions. It is also believed that the efficiency of emulsion breaker use is strongly oil-type dependent (Strøm-Kristiansen et al. 1995).

EFFECTS OF WAVES ON THE BURNING OF OIL

It is clear that *in-situ* burning of water-free oil in the presence of waves is possible (Fingas et al. 1995, Bech et al. 1993, Buist et al. 1983); however, there is little in the literature about the effects of waves on burning processes. Only one previous test has been conducted on burning emulsions in waves (Bech et al. 1993); and the results indicated that wave action had detrimental effects on the burning of a heavily weathered, low water content emulsion. The effects of waves on ISB as a countermeasure at sea are obviously important. The need to understand the processes involved was one of the main goals of this study.

THE PRESENT STUDY

This paper presents preliminary results from a study of ISB with Alaskan oils (crudes and fuels). To date, work has been completed on Phase 1 of the study, comprising a comprehensive series of small-scale burn and emulsion breaking tests with four oils determined to be important in the State of Alaska. Phase 2 work on the effects of waves on small-scale burns of Alaska North Slope (ANS) crude and its emulsions is ongoing and the results obtained so far are reported here. The plan for Phase 3 is to conduct mid-scale emulsion burn tests in a newly-constructed wave tank at ACS this spring or fall.

PROCEDURES

Full details of all experimental methods can be found in the report (S.L. Ross and ACS 1996)

OIL SELECTION, WEATHERING AND EMULSION PREPARATION

The four Alaskan oils selected for Phase 1 of this study were Drift River crude from Cook Inlet, Endicott crude from the North Slope, Pt. McIntyre crude also from the North Slope and IF-30 fuel oil commonly used to bunker vessels. The IF-30 was mixed at the laboratory in a ratio of three parts Bunker-C fuel oil (No. 6) to 1 part middle-distillate cutter oil. IF-30 is similar to No.4 fuel oil.

The burn tests in waves for Phase 2 were conducted using Alaska North Slope crude oil obtained in Prudhoe Bay from Pump Station Number 1 on the Trans-Alaska Pipeline System. The oil/water interfacial tension of the crude was checked to confirm that it had not been highly dosed with surfactants. The measured interfacial tension of 15.2 mN/m confirmed that the sample, although probably containing some surfactants, was not unusual.

Methods of Oil Weathering

Two 19 L samples of each of the four Alaskan oils used in Phase 1 were artificially evaporated to different degrees of weathering. This was accomplished by sparging air from a small compressor through the oil, which was contained in closed 20 L plastic buckets. The vapors were drawn through a pipe in the lid to a fume hood. After an initial period of weathering, the buckets were heated in a water bath to increase the rate of evaporation. It was desired to achieve the same degrees of evaporation as in a previous study of Alaskan oil properties (S.L. Ross 1994). The sparging was continued until the target mass fraction of oil was removed. Preparation of the intermediate degrees of weathered ANS crude oil was accomplished in the same manner.

The 29% weathered ANS crude oil was prepared by sparging air into an open-top 205 L (55 US gallon) drum, containing a pre-measured depth of oil. An electric drum heater was attached to warm the oil and increase the evaporation rate.

Emulsion Formation Test Method

A rotating flask apparatus (Zagorski and Mackay 1982, Hokstad et al. 1993) was used to determine the emulsification tendency and stability of the fresh and weathered oils at room temperature. The tendency of an oil to form an emulsion and the stability of the emulsion formed are measured by two numbers: the Emulsification Tendency Index and the Emulsion Stability Index. If an oil has an Emulsification Tendency Index between 0 and 0.25 it is unlikely to form an emulsion; if it has a Tendency Index between 0.25 and 0.75 it has a moderate

tendency to form emulsions. A value of 0.75 to 1.0 indicates a high tendency to form emulsions.

Similarly, an Emulsion Stability Index of between 0 and 0.25 indicates an unstable emulsion that breaks quickly once removed from the mixing environment; a value of 0.25 to 0.75 indicates a moderately stable emulsion and a value of 0.75 to 1.0 means the oil forms a very stable emulsion that is unlikely to break even after standing for 24 hours.

Emulsion Preparation Method

Emulsions were prepared, both for the emulsion breaker screening test and the in-situ burning tests, by recirculating oil and salt water through a small gear pump. This produces a very stable emulsion containing small, almost mono-disperse water droplets (S.L. Ross 1995). The emulsions produced by the gear pump are such that those created using weathered oil that has a low to moderate Stability Index will, in fact, be very stable.

A volume of 1 L of emulsion with a water content of 50 % was mixed for the emulsion breaker screening tests. The volume and water content of the emulsion mixed for the in-situ burn tests varied according to the specific tests to be performed (see below). The water used to create the emulsions was a 35 parts per thousand (ppt) solution of table salt in tap water.

Emulsion Breaker Screening Method

The purpose of these tests was to determine the effectiveness of selected emulsion breakers on the various weathered oils. Three chemical emulsion breakers, or demulsifiers, were tested:

- ALCOPOL 0 70 PG, produced by Allied Colloid of Great Britain;
- BREAXIT OEB9, produced by Exxon Chemical; and,
- EXO-0894, produced by Petrolite Corporation.

The first two are specially formulated for oil spill use; the third was chosen because it is the demulsifier used in processing Alaska North Slope crude. EXO-0894 was shown to be effective in extending the limits for ISB with ANS emulsions in a previous study (S.L. Ross 1995). The following is a summary of the test procedure using a Burrell Wrist Action Shaker (after Fingas et al. 1993):

- eight 250 mL separatory funnels were filled with 200 mL of salt water (35 ppt);
- fifty percent water content emulsions were prepared and 20 mL was gently injected into the funnels with a syringe;
- the desired amount of emulsion breaker was added to each funnel (either 40 or 400 μ L to give demulsifier:emulsion ratios of 1:500 or 1:5000);

- the funnels were then sealed and allowed to shake with a 1° arc for 3 hours;
- after 15 minutes of settling, samples of the emulsions were removed and mixed until homogeneous; and,
- using a Karl Fischer titrator, the final water content of the emulsion was determined.

The efficiency of the particular emulsion breaker was analyzed by comparing the initial and final water content of the emulsions.

METHODS USED FOR BASELINE BURNS WITHOUT WAVES

The purpose of conducting these burn tests in quiescent conditions with the four Alaskan oils was to establish the natural limits to ignition and burning of emulsions. The parameters that were varied in these burns were: degree of evaporation, emulsion water content and the water temperature in the tank.

Tests were conducted in a 40 cm diameter steel ring floated in the middle of a 11 m x 1.2 m x 1.2 m (L x H x W) wind-wave tank filled with water to a depth of 85 cm. The smoke from the burns was removed with a 200 m³/min fan through 60 cm flexible aluminium duct that was connected to a fume hood suspended 1.5 m above the steel ring. The burns were recorded with two video cameras.

Both the initial mass and volume of the emulsions to be ignited were measured and the air and water temperatures were recorded. As each burn progressed the following were recorded: preheat time (the time taken for the flame to begin to spread from the igniter to the surrounding slick surface); ignition time (the elapsed time for the entire slick area inside the ring to ignite); time to intense burn (the time when the vigorous burn phase began); and, extinction time.

Burn efficiency and burn rate were calculated for each test. Burn efficiency was the ratio of the mass of oil burned to the initial oil mass. Emulsion burn rate was the decrease in the thickness of the slick over the time of the burn. Oil burn rate was a measure of the decrease in the equivalent oil thickness in the slick (as opposed to the emulsion thickness) over the period of the burn.

Burn tests were conducted with emulsions of 25%, 40%, 60% (and in some cases 12.5%) water content. The water temperature in the test tank was maintained at either 3°C or 15°C. If an emulsion was successfully ignited and burned efficiently at 3°C, no further testing with that particular emulsion was needed at 15°C.

The initial volume of emulsion for most of the burn tests was 1900 mL, which corresponded to an initial thickness of 15 mm. The testing with the 18.2% evaporated Pt. McIntyre emulsions was conducted with an initial volume of 1250 mL, or 10 mm thickness, due to the limited volume of this oil that was left after weathering.

The following sequence of ignition sources was followed until the slick was successfully lit:

- i) pre-weighed amount of Heli-torch gelled igniter fuel (75% gasoline: 25% fresh ANS crude);
- ii) 1 mm layer of fresh crude as primer; and,
- iii) 2 mm layer of fresh crude as primer.

Each was initiated with the flame from a propane torch. If the slick failed to ignite the emulsion, it and all emulsions of that oil having higher water contents, were deemed unignitable.

METHODS USED FOR EMULSION BREAKER BURNS WITHOUT WAVES

In these tests emulsion breaker was added to the emulsion types that would not ignite in the previous tests series, and the procedures repeated. The amount of chemical added was 4 mL for slicks of 15 mm initial thickness and 2.5 mL for slicks of 10 mm initial thickness corresponding to a demulsifier: emulsion ratio of approximately 1:500. The emulsion breaker was applied dropwise to the slick and mixed manually with a stirrer for 5 minutes. The slick was then allowed to settle undisturbed for 45 minutes prior to ignition.

IN-SITU BURNING IN WAVES - TEST METHODS

The small-scale study of burning ANS oil and emulsions in waves was conducted in the same tank using the same basic procedures as above, except that the wave generator was turned on immediately after the entire surface area of the slick was on fire. The parameters that were varied during the portions of Phase 2 reported here were: degree of evaporation, initial slick thickness, emulsion water content and waves.

Wave Properties

Three wave settings were used in Phase 2: high energy, low energy, and calm (i.e., no waves). Waves were produced at one end of the test tank with a paddle board powered by a variable speed electric motor. The tank was filled to a level of 85 cm with tap water. A wave absorber was located at the end of the tank opposite the paddle to dissipate wave energy and reduce wave reflection. The characteristics of the waves produced are given in Table 1. It is not possible to translate these to equivalent conditions at sea. Water temperature was kept at between 11 and 14 °C throughout the Phase 2 burn tests reported here.

Wave steepness (height/wavelength) is related to wave energy and was used to quantify the wave conditions. A higher wave steepness corresponds to a higher wave energy. To analyze the effects of waves on combustion, the burn time, burn efficiency, burn rate and amount of burn residue were plotted against wave steepness.

Table 1 - Wave Properties

	Wave Energy Level		
	Calm	Low	High
Height (H cm)	0	9 to 11	14 to 15
Period (s)	0	2	1.25
Wavelength (λ cm)		3.3	2.0
Velocity* (c m/s)	0	1.2	1.7
Steepness (H/ λ)	0	0.03	0.075
Energy** (E J/m ²)	0	122.5	183.8
* Phase velocity: $c^2 = g(1 - \rho_a/\rho_w)\tanh(\kappa h)/\kappa$ where: ρ_a = density of air (kg/m ³) ρ_w = density of water (kg/m ³) $\kappa = 2\pi/\lambda$ (m ⁻¹) g = force of gravity (N/kg)			
** Energy: $E = \rho_w g (H/2)^2 / 4$			

RESULTS AND DISCUSSION

EMULSION TESTS

Emulsion Formation Tendency and Stability

The results from the emulsion tendency and stability testing for the four Alaskan oils used in Phase 1 and the ANS crude used in Phase 2 are presented in Table 2.

The results show that all of the first four oils had a high tendency to form emulsions under the test conditions; furthermore, all emulsions were very stable except those formed by the fresh Pt. McIntyre crude and the fresh Drift River. After about 16% volume loss to evaporation, the ANS crude oil began to exhibit a tendency to form an emulsion: only after 29% evaporation did the emulsions formed remain stable for 24 hours. This is typical of ANS crude, which is regularly treated with various production and pipelining chemicals, including emulsion breakers.

Table 2 - Emulsion Formation Tendency and Stability Test Results

Oil	Degree of Weathering (volume % loss)	Tendency Index f_0	Stability Index f_{∞}
Endicott	0	1	1
	9.1	1	1
	17.4	1	1
Pt. McIntyre	0	0.9	0.2
	9.1	1	1
	18.2	1	1
Drift River	0	1	0.2
	23.8	1	1
	35.4	1	1
IF-30	0	1	1
Alaska North Slope	0	0	0
	9.6	0	0
	11.3	0	0
	15.9	0.9	0
	24.9	0.9	0
	25.0	0.9	0
	29.0	1.0	1.0

Emulsion Breaker Effectiveness

The results from the emulsion breaker effectiveness tests are given in Table 3. Listed is the water removal (as a percentage of the initial water content), averaged over all the degrees of evaporation for a given oil, for each emulsion breaker. The initial water content of the test emulsions was 50% by volume.

The results indicate that, overall, EXO-0894 was the most effective at breaking the emulsions, as was previously found for the ANS crude (S.L. Ross 1995). Alcopol was almost as good, or better, with some emulsions.

Table 3 - Emulsion Breaker Test Results

Oil	Demulsifier	Average Water Removal (%)
Pt. McIntyre	Brexit	23.3
	Alcopol	28.8
	EXO-0894	27.2
Endicott	Brexit	6.6
	Alcopol	24.3
	EXO-0894	30.6
Drift River	Brexit	2.0
	Alcopol	13.5
	EXO-0894	19.4
IF-30	Brexit	3.1
	Alcopol	0.0
	EXO-0894	3.8

The emulsion breaker screening test using the Burrell Wrist Action Shaker was less than ideal. For the emulsions tested, which were all highly stable, it was found that no breaking was observed during the three hour shaking period; this was due to the fact that the specified 1° shaking arc did not disturb the viscous emulsions enough to prompt the mixing of the breaker into the emulsion. Only a slight darkening of the emulsion was seen at the location where the breaker was originally applied. There was also no breaking observed during the 15 minute settling period. All of the breaking occurred during the final step of the test when, according to procedure, the emulsion was removed from the separatory funnel and stirred to ensure homogeneity prior to the water content analysis. Consideration should be given to using a different test in the future, perhaps using the rotating flask apparatus (Delmazzone et al. 1995).

BASELINE BURNS WITH NO WAVES

Forty-two baseline burns were conducted to determine the limits to ignition and burning of the emulsified Alaskan oils. Initially burns were conducted at a tank water temperature of 3°C; later the temperature was increased to 15°C to determine the effect of temperature on the ignitability limits.

Drift River Crude Oil

The results of the baseline burn tests with Drift River crude oil emulsion at a temperature of 3°C are summarized in Table 4.

Table 4 - Emulsion Burns with Drift River Crude Oil at 3°C

Degree of Weathering (%)	Water Content (%)	Burn Rate (mm oil / min)	Burn Efficiency (%)
0	25	0.9	92.3
0	40	1.0	92.0
0	60	0.7	79.6
23.8	25	0.4	41.8
23.8	40	Unignitable	
35.4	25	0.3	61.6
35.4	40	Unignitable	

The fresh Drift River crude was successfully ignited at all the tested water contents with the gelled gasoline/crude igniter. All of the burns were efficient. Both the 23.8% and 35.4% weathered Drift River could only be ignited at 25% water content and both required 2 mm of fresh crude primer to achieve successful ignition. The burn of the 25% water, 23.8% evaporated oil exhibited a very weak intense burn phase. The burn with 35.4% evaporated oil in a 25% emulsion was very weak, with the flames surging up and dying back continuously, until a strong intense burn phase was reached. This surging phenomenon is believed to be indicative of the oil supply rate from emulsion breaking being less than the oil vaporization rate needed to support continuous combustion (S.L. Ross 1995). All higher water contents were deemed unignitable at this temperature.

All of the fresh Drift River emulsions were ignited at 3°C, therefore, no further testing was conducted at 15°C. Table 5 presents the results of the baseline burn tests with 23.8% and 35.4% evaporated Drift River emulsions at 15°C.

Table 5 - Emulsion Burns with Drift River Crude Oil at 15°C

Degree of Weathering (%)	Water Content (%)	Burn Rate (mm oil / min)	Burn Efficiency (%)
23.8	25	0.4	46.0
23.8	40	0.7	76.4
23.8	60	0.2	38.5
35.4	25	0.4	47.7
35.4	40	Unignitable	

The increase in water temperature allowed all the emulsions of the 23.8% evaporated crude tested to be successfully ignited. The 25% water emulsion was ignited with 1 mm of fresh crude (as opposed to 2 mm at 3°C). The low efficiency of the 25% emulsion burn, compared to that of the 40%, may be a result of the lower ignition power used; although, at 3°C a 2 mm primer layer also resulted in a 42% burn efficiency. The 40% and 60% water emulsions required 2 mm of fresh crude for ignition. The 40% emulsion burned well, but the 60% emulsion burned poorly. The increase in water temperature had no effect on the ignitability of the 35.4% evaporated emulsions. As with the tests at 3°C, only the 25% water content emulsion ignited. The same phenomenon of surging flames, as seen at the lower temperature, was observed at the higher temperature. All higher water contents were deemed unignitable at 15°C.

Overall, Drift River emulsion slicks ignited and burned at fairly high degrees of evaporation and emulsification. Both burn efficiency and burn rate generally decreased with an increase in the degree of weathering. Increasing the temperature with the 23.8% weathered Drift River crude, permitted the burning of slicks that were unignitable at the lower temperature; however, the increase in temperature had no effect on the limits of ignition of the 35.4% evaporated Drift River emulsions.

Endicott Crude Oil

The results of the baseline burn tests with Endicott crude oil emulsions at a water temperature of 3°C are presented in Table 6.

Table 6 - Emulsion Burns with Endicott Crude Oil at 3°C

Degree of Weathering (%)	Water Content (%)	Burn Rate (mm oil / min)	Burn Efficiency (%)
0	25	0.4	92.2
0	40	Unignitable	
9.1	25	0.7	91.60
9.1	40	Unignitable	
17.4	12.5	0.9	92.0
17.4	25	0.5	89.7
17.4	40	Unignitable	

For the fresh oil, the 25% water content ignited and burned successfully using the gelled fuel igniter. The flames were quite weak for the first 20 minutes of the burn, although an intense burn phase and a high burn efficiency were eventually achieved. The 40% emulsion appeared to be going to ignite but, once the 2 mm of fresh crude

was consumed, the burn was not sustained; and the emulsion was considered unignitable. All higher water contents were also deemed unignitable. The 25 % water emulsion of the 9.1 % evaporated Endicott was ignited with 2 mm of fresh crude and burned very well. It was not possible to ignite the 40 % water emulsion. The gelled fuel igniter was successful in igniting the 12.5 % water emulsion of the 17.4 % evaporated Endicott, which burned efficiently. A 2 mm layer of fresh crude was able to ignite the 25 % water emulsion, but not the 40 %.

Table 7 lists the results of the baseline test burns with Endicott crude oil emulsions at 15°C.

Table 7 - Emulsion Burns with Endicott Crude Oil at 15°C

Degree of Weathering (%)	Water Content (%)	Burn Rate (mm oil/ min)	Burn Efficiency (%)
0	40	0.3	54.1
0	60	0.6	70.5
9.1	25	0.5	89.9
9.1	40	Unignitable	
17.4	25	0.2	26.5
17.4	40	Unignitable	

All the emulsions of the fresh crude tested were ignited successfully at the higher temperature, using 2 mm of fresh crude as the ignition source. For both the 9.1 % and 17.4 % evaporated Endicott, the increase in temperature had no effect on the limits to ignition or on the required ignition source; only the 25 % water content emulsions were ignitable and all higher water contents were deemed unignitable.

In general, the emulsified slicks of Endicott crude were more difficult to ignite than those of Drift River crude.

Pt. McIntyre Crude Oil

The results of the baseline ignition and burning tests with Pt. McIntyre crude oil emulsions at a water temperature of 3°C are presented in Table 8.

Table 8 - Emulsion Burns with Pt. McIntyre Crude Oil at 3°C

Degree of Weathering (%)	Water Content (%)	Burn Rate (mm oil/min)	Burn Efficiency (%)
0	25	0.5	59.8
0	40	Unignitable	
9.1	25	0.4	50.9
9.1	40	Unignitable	
18.2	12.5	0.5	54.0
18.2	25	Unignitable	

Ignition was achieved only with the 25% water content emulsion for both the fresh and 9.1% weathered oils. Neither burn was efficient. Only the 12.5% water content emulsion was successfully ignited at 18.2% weathering and required 2 mm of fresh crude. All higher water contents were deemed unignitable at this temperature.

The results of the baseline burn tests with Pt. McIntyre crude emulsions at 15°C are presented in Table 9.

Table 9 - Emulsion Burns with Pt. McIntyre at 15°C

Degree of Weathering (%)	Water Content (%)	Burn Rate (mm oil / min)	Burn Efficiency (%)
0	25	0.7	88.0
0	40	Unignitable	
9.1	25	0.5	86.9
9.1	40	Unignitable	
18.2	12.5	0.6	88.0
18.2	25	Unignitable	

The increase in temperature had no effect on the ignition limits of the emulsions of Pt. McIntyre crude; however, it did increase the burn efficiency for those emulsions that were successfully ignited. The fresh and 9.1% evaporated emulsions were ignited at 25% water content; 18.2% evaporated emulsion was ignited at only the 12.5% water content. All higher water contents were deemed unignitable. The fresh

emulsion was ignited with 1 mm of fresh crude. The 9.1% weathered emulsion required 2 mm of fresh crude for ignition.

At the higher temperature the burn rates and burn efficiencies remained relatively constant for all degrees of weathering. The increase in water temperature resulted in a considerable increase in the burn efficiency of the ignited slicks, although the burn rate did not appear to be as greatly affected. In general, the Pt McIntyre crude oil emulsions proved to be the most difficult of the crudes to ignite and burn.

IF-30

The results of the baseline burn tests with IF-30 crude oil emulsions at a water temperature of 3°C are presented in Table 10.

Table 10 - Emulsion Burns with IF-30 Fuel Oil at 3°C

Degree of Weathering (%)	Water Content (%)	Burn Rate (mm oil/min)	Burn Efficiency (%)
0	12.5	1.1	87.6
	25.0	0.4	77.8
	40.0	Unignitable	

The 12.5% water emulsion was ignited with the gelled fuel and burned successfully. The 25% water emulsion was more difficult to ignite, requiring 2 mm of fresh crude; the burn was weak, with the flames dying back then surging up repeatedly, until the intense burn phase was reached (at 17 minutes into the burn). The 40% water emulsion was unignitable.

The results of the baseline burns with IF-30 emulsions at 15°C are presented in Table 11.

Table 11 - Emulsion Burns with IF-30 Fuel Oil at 15°C

Degree of Weathering (%)	Water Content (%)	Burn Rate (mm oil/min)	Burn Efficiency (%)
0	25	Unignitable	

It was likely experimental variability that caused the anomalous result of no ignition of the 25% water emulsion at 15°C yet successful ignition at 3°C. In general, the

IF-30 emulsions proved the most difficult to ignite. This is not surprising, since IF-30 contains no light ends.

EMULSION BREAKER BURNS WITH NO WAVES

A total of 27 emulsion breaker burns were conducted with emulsions that were found to be unignitable during the baseline burn tests. The emulsion breaker EXO-0894 was used for the majority of the burn tests. For comparison, higher temperature burns were conducted with Alcopol and EXO-0894 for Endicott emulsions and Breaxit and EXO-0894 for Pt. McIntyre emulsions. The emulsion breaker test raw data indicated that Alcopol might work better with some Endicott emulsions and Breaxit might work better with some Pt. McIntyre emulsions. The full data sets for the emulsion breaker burns may be found in the report (S.L. Ross and ACS 1996).

Drift River Crude Oil

The results of burns with EXO-0894 on Drift River crude emulsions at 3°C are presented in Table 12. None of these emulsions could be ignited without the addition of a chemical breaker.

Table 12 - Emulsion Burns with Drift River Crude Oil and EXO-0894 at 3°C

Degree of Weathering (%)	Water Content (%)	Burn Rate (mm/min)	Burn Efficiency (%)
23.8	40	0.0	4.7
23.8	60	0.4	82.9
35.4	40	0.0	0
35.4	60	0.6	84.30

The addition of EXO-0894 to the 40% water emulsions of the 23.8% and 35.4% weathered Drift River had very little effect on the ignitability. Both can essentially be considered unignitable. Interestingly, the emulsion breaker did cause the 60% water emulsion to break enough to be ignitable. Apparently the 40% water emulsion resists the emulsion breaking surfactant effect. This phenomenon of treated 60% water emulsion burning better than treated 40% emulsions has been observed before with the Alaskan North Slope crude oil (S.L. Ross, 1995). It may be that the 40% water content represents a situation in which the water droplets in the emulsion resist coalescence, even when the chemical barriers to coalescence are removed by the surfactant. It should be remembered that, in a slick at sea, emulsification occurs quite quickly once an oil spill reaches the degree of weathering that makes it

susceptible to emulsification. A 40% water content would not exist for very long at sea; rather the slick would quickly reach its maximum water content of 60 to 80%.

Overall, the application of the emulsion breaker greatly extended the limits to ignition for the Drift River crude.

Endicott Crude Oil

The results of the ignition and burning tests with Endicott crude oil emulsion with the addition of EXO-0894 are listed in Table 13. None of these emulsions could be ignited without the application of emulsion breaker.

Table 13 - Emulsion Burns with Endicott Crude Oil and EXO-0894 at 3°C

Degree of Weathering (%)	Water Content (%)	Burn Rate (mm/min)	Burn Efficiency (%)
0	60	0.4	84.3
9.1	40	0.5	88.5
9.1	60	0.5	81.4
17.4	40	0.0	0
17.4	60	0.0	0

All tested water contents for the fresh and 9.1% weathered Endicott emulsions ignited and burned successfully with the addition of 4 mL of EXO-0894, using 2 mm of fresh crude as the igniter. The 17.4% evaporated emulsions appeared to ignite but once the fresh crude primer was consumed they did not burn long enough to reduce the weight of residue below the initial weight of oil in the emulsion. The 60% water emulsion of the 17.4% evaporated Endicott was tested and exhibited the same behavior.

Table 14 presents the results of the burn tests with Endicott crude oil emulsions, using alternative emulsion breakers and at a higher water temperature of 15°C.

No significant difference in ignitability or burn efficiency was observed between the burns with Alcopol and the burns with EXO-0894. The increase in water temperature did not have any noticeable effect on the ignitability or burn efficiency for this oil.

Table 14 - Emulsion Burns with Endicott Oil and Alcopol or EXO-0894 at 15°C

Degree of Weathering (%)	Water Content (%)	Emulsion Breaker	Burn Rate (mm/min)	Burn Efficiency (%)
9.1	60	Alcopol	0.5	74.6
9.1	60	EXO-0894	0.5	80.7
17.4	40	Alcopol	Unignitable	
17.4	40	EXO-0894	Unignitable	

The application of the emulsion breaker considerably extended the limits to ignition of Endicott crude emulsions, although a limit still existed. It should be kept in mind that, in the real world, slicks of Endicott crude would begin to emulsify immediately on being spilled. The formation of the emulsion would be fairly rapid (a few hours perhaps) and, once a high water content was reached, the slick would become unignitable. Evaporation of the oil would also slow considerably at this point. The formation of a 60% water content emulsion can increase the time required for the parent oil to reach a given level of evaporation by a factor of 5 to 10 (Ross and Buist 1995). Adding emulsion breakers could allow ignition of fully emulsified slicks of 9% evaporated oil. This would be increasing the available response time for ISB operations from less than a day to a week or so. This is a significant improvement.

Point McIntyre Crude Oil

The results of the emulsion burns of the Pt. McIntyre crude oil with emulsion breakers applied are presented in Table 15. None of these emulsions could be ignited without the addition of an emulsion breaker.

Table 15 - Emulsion Burns with Pt. McIntyre Crude Oil and EXO-0894 at 3°C

Degree of Weathering (%)	Water Content (%)	Burn Rate (mm/min)	Burn Efficiency (%)
0	40	0.5	57.7
0	60	0.0	0
9.1	40	0.0	0
9.1	60	Unignitable	
18.2	25	0.4	54.1
18.2	40	Unignitable	

For the fresh oil, the 40% water content emulsion was successfully ignited and burned with 2 mm of fresh crude oil, while the 60% water emulsion was unignitable. EXO-0894 was unable to expand the ignition limits of the 9.1% weathered emulsions; the attempts to ignite both the 40% and 60% water emulsion were unsuccessful. The difference between a burn rate of 0.0 mm/min and "unignitable", as seen in Table 15, is as follows. For the 40% water emulsion of 9.1% weathered crude the fire burned for more than the time required to consume the 2 mm layer of fresh crude primer but did not consume enough oil to reduce the weight of residue to below the initial mass of oil in the emulsion. In the case of the 60% water burn, the fire extinguished immediately after the 2 mm of fresh crude primer was consumed.

Ignition of the 18.2% evaporated Pt. McIntyre at 25% water content was achieved with 2 mm of fresh crude. The 40% emulsion was unignitable and because the 60% water, 9.1% evaporated emulsion was unignitable, this and all higher water content emulsions were deemed unignitable at this temperature.

Table 16 presents the results of the burn tests with Point McIntyre crude oil, using alternative emulsion breakers, at a water temperature of 15°C.

Table 16 - Emulsion Burns with Pt. McIntyre & Breaxit or EXO-0894 at 15°C

Degree of Weathering (%)	Water Content (%)	Emulsion Breaker	Burn Rate (mm/min)	Burn Efficiency (%)
9.1	40	Breaxit	0.0	0
9.1	40	EXO-0894	Unignitable	
9.1	60	Breaxit	Unignitable	
9.1	60	EXO-0894	Unignitable	
18.2	25	Breaxit	0.4	72.9
18.2	25	EXO-0894	0.4	81.30

Neither the increase in water temperature nor the use of an alternative emulsion breaker was able to substantially affect the ignitability or burn efficiency of the 9.1% evaporated Point McIntyre.

A modest increase in burn efficiency was observed at the higher temperature for the 25% water emulsion of the 18.2% evaporated crude for both emulsion breakers.

Both the burn rate and efficiency was approximately the same for the two emulsion breakers.

In general, chemical emulsion breaker addition did not significantly increase the ignitability of Pt. McIntyre crude oil emulsions. The reason for this does not appear to relate to oil volatility (all three Phase 1 crudes had similar Flash Points); but, may be related to oil rheology. Pt. McIntyre crude had the highest viscosity of the three crudes. High oil viscosity likely plays a role in both emulsion viscosity and in emulsion breaking. Oil forms the continuous phase in a water-in-oil emulsion. In order to generate a layer of water-free oil on top of the emulsion the water droplets must sink through the continuous phase. The settling velocity of the water droplets decreases with increasing oil viscosity.

It may also be possible that Pt. McIntyre crude is resistant to the emulsion breaking chemicals and dosages used in this study, but would break more easily if different surfactants or dosages were used. One idea would be to get information on which breakers and concentrations are used for a given oil in production operations, as was the case for EXO-0894 usage with ANS crude emulsions (S.L. Ross 1995). The results for the Pt. McIntyre crude highlight the need to conduct these types of tests for each individual oil being considered for ISB. Just because the techniques work effectively for one oil/breaker combination does not mean they will work for another.

IF-30

The results of the ignition and burning tests with IF-30 fuel oil emulsion with the addition of EXO-0894 are listed in Table 17.

Table 17 - Emulsion Burns with IF-30 Fuel Oil with EXO-0894 at 3°C

Degree of Weathering (%)	Water Content (%)	Burn Rate (mm oil/min)	Burn Efficiency (%)
0	40	0.4	77.8
0	60	Not Stable	

The addition of 4 mL of EXO-0894 enabled the ignition of the 40% water IF-30 emulsion. The 60% water emulsion was not stable and was, therefore, not tested.

Alternate emulsion breakers were not tested on IF-30 emulsions.

***IN-SITU* BURNING OF ALASKA NORTH SLOPE CRUDE OIL IN WAVES**

A total of 43 burns were performed as summarized in Table 18.

Table 18 - Laboratory-scale Wave Burn Test Results

Exp #	% Evap	% Water	Initial thickness (mm)	Wave energy	Wave period (s)	Wave height (cm)	λ (m)	Residue Mass (g)	Burn Time (min)	Burn Rate (mm oil/min)	Burn Efficiency (%)
1	0	0	2	low	2.0	10	3.3	183.3	1.45	0.2	13.7%
2	0	0	5	low	2.0	10	3.3	174.9	3.45	1.0	68.0%
3	0	0	10	low	2.0	10	3.3	248.5	5.95	1.3	77.7%
4	0	0	20	low	2.0	10	3.3	331.8	11.03	1.4	84.1%
5	0	0	2	high	1.25	15	2	188.2	1.83	0.2	17.5%
6	0	0	5	high	1.25	15	2	177.7	3.28	1.0	67.7%
7	0	0	10	high	1.25	15	2	283.8	4.73	1.6	75.8%
8	0	0	20	high	1.25	15	2	411.7	8.73	1.9	81.5%
9	0	0	2	none	0	0	0	178.8	2.03	0.2	18.9%
10	0	0	5	none	0	0	0	179.7	3.92	0.9	67.5%
11	0	0	10	none	0	0	0	213.6	7.42	1.1	80.5%
12	0	0	20	none	0	0	0	240.8	14.10	1.2	88.9%
13	14.86	0	5	low	2.0	10	3.3	143.1	3.28	0.9	70.1%
13b	14.73	0	5	low	2.0	10	3.3	210.0	3.23	1.0	64.0%
14	14.86	0	10	low	2.0	10	3.3	200.5	7.00	1.2	82.6%
15	14.86	0	20	low	2.0	10	3.3	300.0	13.80	1.2	86.6%
16	14.86	0	5	high	1.25	15	2	172.7	3.07	1.4	74.7%
16b	14.73	0	5	high	1.25	15	2	251.7	3.23	0.9	55.7%
17	14.86	0	10	high	1.25	15	2	251.3	4.85	1.5	77.2%
18	14.86	0	20	high	1.25	15	2	286.3	10.18	1.7	87.5%
19	14.73	0	10	none	0	0	0	214.7	6.20	1.2	79.5%
19b	14.73	0	10	none	0	0	0	225.9	6.08	1.3	80.3%
20	14.73	0	20	none	0	0	0	177.4	15.33	1.2	92.4%
21	14.73	0	5	none	0	0	0	155.0	3.37	1.1	72.9%
22	26.8	0	5	none	0	0	0	118.7	4.42	0.9	79.8%
23	26.8	0	10	none	0	0	0	134.7	6.15	1.4	88.3%
24	26.8	0	20	none	0	0	0	143.4	16.10	1.2	93.9%
25	26.8	0	5	low	2.0	10	3.3	135.0	2.75	1.4	77.0%
26	26.8	0	10	low	2.0	10	3.3	174.9	5.97	1.4	85.1%
27	26.8	0	20	low	2.0	10	3.3	248.2	12.23	1.4	89.0%
28	29	0	20	none	0	0	0	123.8	17.83	1.1	94.7%
29	29	0	20	low	2.0	10	3.3	75.8	17.02	1.1	96.8%
30	29	0	20	high	1.25	15	2	409.0	11.00	1.5	82.6%
31	29	12.5	20	none	0	0	0	598.4	15.08	1.0	74.8%
32	29	12.5	20	low	2.0	10	3.3	147.0	18.72	1.0	93.8%
33	29	12.5	20	high	1.25	15	2	442.3	15.85	1.0	81.6%
34	29	25	20	none	0	0	0	953.2	25.15	0.4	55.4%
35	29	25	20	low	2.0	10	3.3	1970.0	10.28	0.3	15.0%
36	29	25	20	high	1.25	15	2	2085.0	5.02	0.4	11.0%
37	29	40	20	none	0	0	0	1991.9	7.97	0.4	15.2%
38	29	40	20	low	2.0	10	3.3	2315.0	4.60	0.1	1.5%
39	29	40	20	none	0	0	0	1940.0	7.78	0.4	17.4%
40	26	0	5	high	1.25	15	2	170.0	3.27	1.0	70.0%
42	26	0	20	high	1.25	15	2	286.5	9.20	1.9	87.8%
43	26	0	10	high	1.25	15	2	251.8	4.77	1.8	78.4%

Results with Water-Free Oil in Waves

For burns of fresh ANS crude the burn rate (Figure 1a) was not appreciably affected by waves for thin slicks (2 and 5 mm); however, for the 10 and 20 mm slicks burn rate increased with increasing wave steepness. Burn time (Figure 1b) decreased with increasing wave steepness; the effect was more pronounced as slick thickness increased. Burn efficiency (Figure 1c) was little affected by increasing wave steepness; however, the amount of residue remaining after a burn (Figure 1d) increased appreciably with increasing wave steepness. The increase in residue mass was only a small percent of the initial oil mass.

For burns using 15% weathered ANS crude (note that 2 mm slicks were not tested since they were found to be unignitable at this degree of weathering) the burn rate (Figure 2a) generally increased with increasing wave steepness. Burn time (Figure 2b) was not appreciably affected by wave steepness for the 5 mm slicks and only slightly reduced for the 10 mm slicks; the 20 mm slicks showed a definite decrease in burn time with increasing wave steepness. The effect of waves on burn efficiency (Figure 2c) was not clear due to scatter in the data. The amount of residue remaining also showed a high degree of scatter; however, a trend of increasing residue with increasing wave steepness seems apparent.

For the 26% weathered ANS crude (again, no 2 mm slicks were tested) the burn rate (Figure 3a) increased significantly with increasing wave steepness for both the 10 and 20 mm burns. Results for the 5 mm slicks showed an increase in burn rate from calm to low wave energy, but a sharp decrease in burn rate for high energy waves. This may represent the approach of a limit to burning of this thickness and degree of weathering, or it may be as a result of experimental error. The burn times (Figure 3b) for the 5 and 10 mm slicks decreased slightly with increased wave steepness; the burn time for the 20 mm slicks decreased significantly with increasing waves. Burn efficiency (Figure 3c) decreased significantly with increasing wave steepness for all slick thicknesses. Likewise, the amount of burn residue remaining (Figure 3d) increased with increasing wave energy.

Results to Date with Emulsions in Waves

The few burns conducted so far with 29% weathered ANS emulsions (with 12.5% and 25% water content) were done with 20 mm thick slicks. The burn rate (Figure 4a) for the water-free oil increased with wave steepness; but, not for the 12.5% and 25% water content emulsions. The burn rate for the 25% emulsions was significantly lower than either the 0% or 12.5% water content emulsion burns. Burn time (Figure 4b) decreased slightly with increasing wave energy for the water-free slicks and remained relatively constant for the 12.5% water emulsion slicks; sharp decreases in burn times with increasing wave steepness were observed for the 25% water content emulsions. The burn efficiency (Figure 4c) was not greatly affected by waves in the case of the water-free and 12.5% water content emulsion; but, a sharp decrease in efficiency for the 25% water content emulsions is apparent. A similar trend can be seen in the amount of residue remaining (Figure 4d).

FIGURE 1 - FRESH ANS BURNS IN WAVES

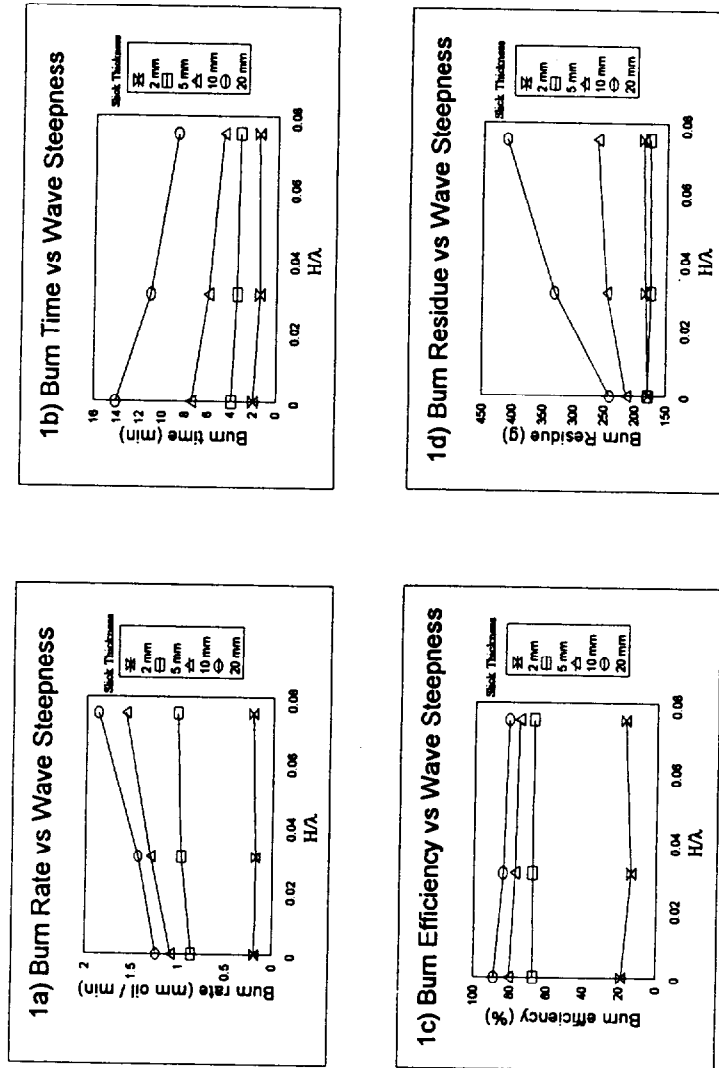


FIGURE 2 - 15% EVAPORATED ANS BURNS IN WAVES

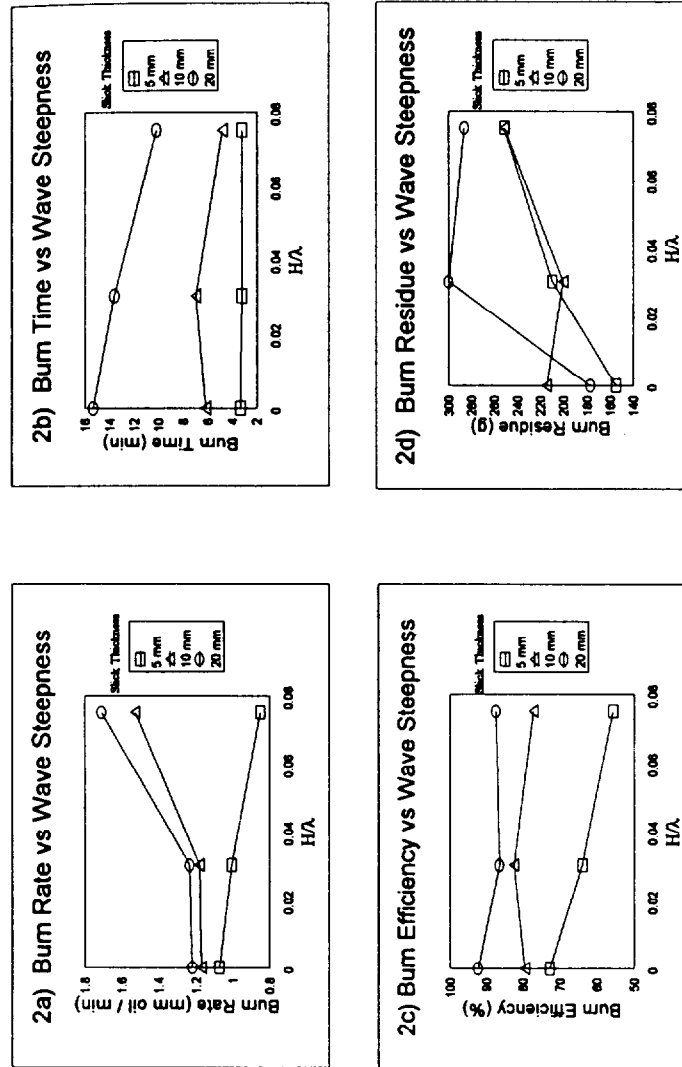


FIGURE 3 - 26% EVAPORATED ANS BURNS IN WAVES

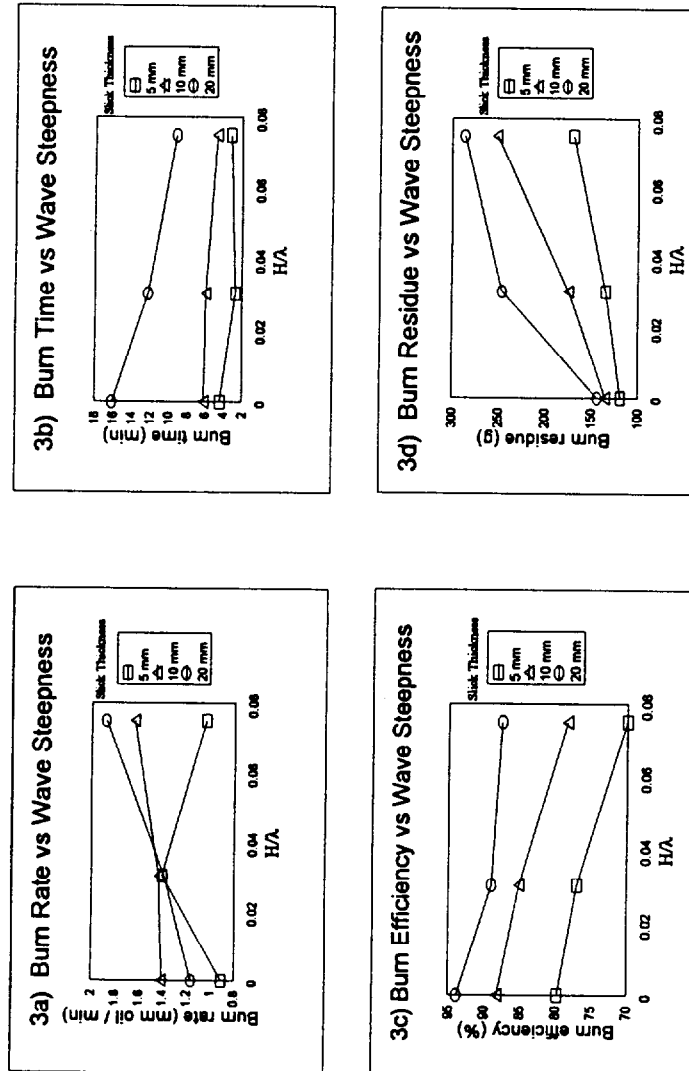
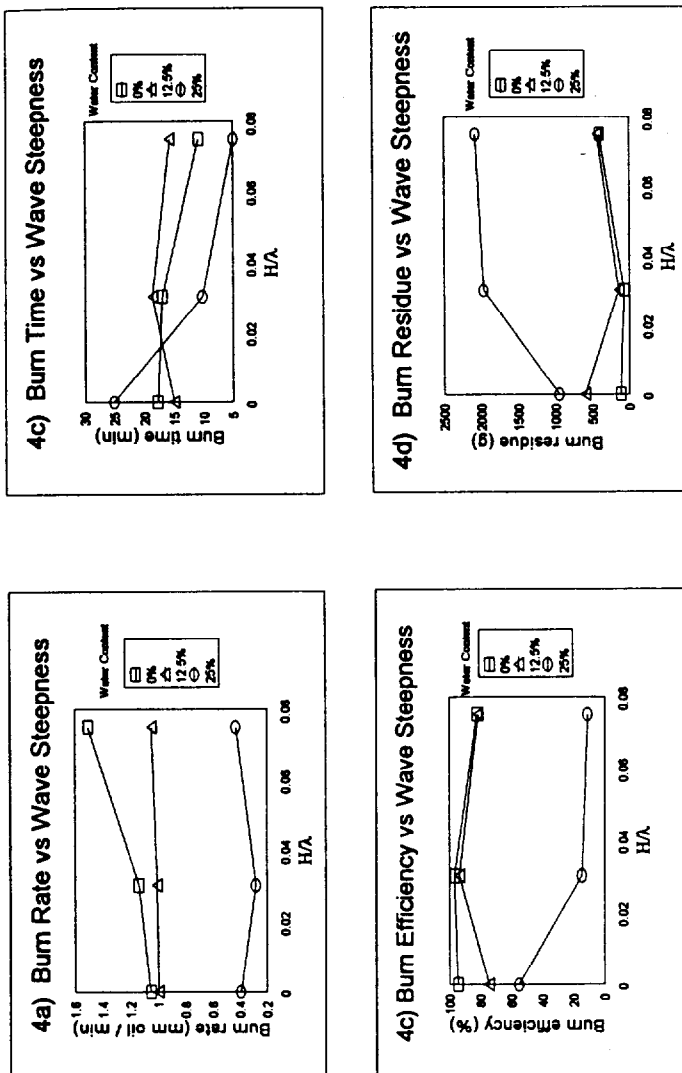


FIGURE 4 - 29% EVAPORATED EMULSIFIED ANS BURNS IN WAVES (20 mm Slicks)



Overall the trends observed to date include an increase in burn rate with increasing wave steepness for thicker slicks (10 - 20mm) of water-free fresh and weathered ANS and low water content emulsions. The reason for this is not apparent at present, but may be related to the mixing action of the waves transferring fresh fuel from the interior of the burning slick to the surface.

Burn times generally decreased and burn residue amounts generally increased with increasing wave steepness for all slick thicknesses, degrees of evaporation and emulsion water contents. This may relate to enhanced heat transfer through the slick caused by wave action resulting in earlier extinction. It may also be a result of wave induced mixing action depleting the light ends of the remaining slick, and thus raising its Fire Point, faster than in a quiescent situation, resulting in quicker extinction.

Burn efficiency appears to be reduced (i.e., the amount of residue increased) by wave action. The effect appears to be magnified by increasing levels of evaporation and water content.

Emulsion water hindered the burning process with significant decreases in burn efficiency and burn time for 25% water content when compared with 0% and 12.5% emulsions. It is nonetheless significant that 25% water content emulsions of heavily weathered ANS were successfully burned in waves.

SUMMARY OF PRELIMINARY RESULTS TO DATE

As expected, the ignition and burning of all four oils selected for Phase 1 of this study was limited by the formation of water-in-oil emulsions. As has been noted in other studies, the burning of emulsions in-situ was found to be oil-specific, with some oils (e.g., Drift River) being much easier to ignite and burn than others (e.g., Pt McIntyre). Evaporation also appears to play a strong role in emulsion burning; increased weathering decreased ignitability and burn efficiency. Increased water content also reduced ignitability, oil burn rate and burn efficiency.

The application of chemical breakers to emulsions of the four oils extended the limits of ignition and burnability. The chemical EXO-0894 appeared to be the best of the three tested on the four oils, although the others may be equally suitable, or better, for certain emulsions. The efficacy of emulsion breaker addition in extending the limits of ignition and efficient burning also appears to be oil-related (and perhaps, to a lesser extent, breaker-related). The use of EXO-0894 considerably extended the limits for some oils (e.g., Drift River) but only had a marginal effect on others (e.g., Pt. McIntyre). There are likely two reasons for this: the first is the form of the emulsion. For those situations where the emulsion breaker did not greatly increase the limits of burning, the parent oil was viscous and the emulsion was a highly viscous, near-solid gel when poured onto the water. Even after the manual mixing of the emulsion breaker, it was visually apparent that little was happening over the 45 minute settling period. Thus, the ineffectiveness of the breaker may be related to its inability to penetrate into and act on viscous, semi-

solid emulsions. It should also be kept in mind that the emulsions used in these experiments were intentionally created to be very stable.

In-situ burning of emulsions is also sensitive to ambient temperature. Generally, as temperatures increased, ignition of emulsions became easier and burn efficiency increased. This effect appears to be oil-specific as temperature increases had large effects on the burning of emulsions of some oils (e.g., Drift River and Endicott) but almost no effect on others (e.g., Pt. McIntyre). It is not clear what properties of the emulsions control this behavior, although vapor pressure and viscosity are likely candidates.

This leads to the second possible reason for the ineffectiveness of the breaker - the fact that the settling period in these tests involved quiescent conditions. The presence of wave action during this settling period that "works" the emulsion (and chemical) could have advantages to the breaking process. Static tests may not be the ideal measure of the efficacy of emulsion breaker addition in improving the in-situ burning of emulsions.

It was determined that waves had an effect on the burning of fresh, weathered and slightly emulsified ANS crude oil. Burn rates increased with increasing wave steepness (energy) as did the amount of residue remaining after extinction. Burn efficiency and burn time both decreased with increasing wave steepness. The effect was most pronounced for heavily weathered oils (> 26% evaporated) and emulsions (12.5% and 25% water).

ACKNOWLEDGEMENTS

The funding for this study was provided by the Alaska Department of Environmental Conservation (ADEC). The authors would also like to thank the owner companies of Alaska Clean Seas for their support of this study. These are: Alyeska Pipeline Service Co., Amerada Hess, ARCO, BP, Exxon and Unocal.

DISCLAIMER

The research described in this paper was supported by the Alaska Department of Environmental Conservation. However, the findings and conclusions presented by the authors are their own and do not necessarily reflect the views or position of the Department.

REFERENCES

Bech, C., P. Sveum, and I. Buist. 1993. The effect of wind, ice and waves on the *in-situ* burning of emulsions of aged oils. Proceedings of the 16th AMOP Technical Seminar, June 7-9, Calgary, Alberta. Environment Canada, Ottawa, Ontario. pp 735-748.

Buist, I.A., W.M. Pistruzak, S.G. Potter, N. Vanderkooy and I.R. McAllister. 1983. The development and testing of a fireproof boom. Proceedings of the Sixth AMOP Technical Seminar. Environment Canada, Ottawa. pp. 70-84.

Delmazzone, C., C. Bocard and D. Ballerini. 1995. IFP procedure for testing and developing water-in-crude oil emulsion inhibitors. Proceedings of the Eighteenth AMOP Technical Seminar. Environment Canada, Ottawa. pp. 317-328.

Fingas, M.F. G. Halley, F. Ackerman, R. Nelson, M. Bissonnette, N. Laroche, Z. Wang, P. Lambert, K. Li, P. Jokuty, G. Sergy, E.J. Tennyson, J. Mullin, L. Hannon, R. Turpin, P. Campagna, W. Halley, J. Latour, R. Galarneau, B. Ryan, D.V. Aurand and R.R. Hiltabrand. 1995. The Newfoundland Offshore Burn Experiment — NOBE. Proceedings of the 1995 Oil Spill Conference. API, Washington, D.C. pp. 123-138.

Fingas, M., B. Fieldhouse, I. Bier, D. Conrad and E. Tennyson. 1993. Testing water-in-oil emulsion breakers. In *Formation and breaking of water-in-oil emulsions: Workshop proceedings*. MSRC report 93-018. Washington. pp. 89-96.

Guenette, C., P. Sveum, C. Bech and I. Buist. 1995. Studies of in-situ burning of emulsions in Norway. Proceedings of the 1995 Oil Spill Conference. API, Washington, D.C. pp. 115-122.

Guenette, C., P. Sveum, I. Buist, T. Aunaas and L. Godal. 1994. In-Situ Burning of Water-in-Oil Emulsion. Report to NOFO, ACS, MSRC, Pluto and Amoco. SINTEF Report No. STF21 A94053 Trondheim.

Hokstad, J., P. Daling, A. Lewis and T. Strøm-Kristiansen. 1993. Methodology for testing water-in-oil emulsions and demulsifiers. In *Formation and breaking of water-in-oil emulsions: Workshop proceedings*. MSRC report 93-018. Washington. pp. 239-254.

Ross, S., and I. Buist. 1995. Preliminary laboratory study to determine the effect of emulsification on oil spill evaporation. Proceedings of the Eighteenth AMOP Technical Seminar. Environment Canada, Ottawa. pp. 91-110.

S.L. Ross Environmental Research Ltd. and Alaska Clean Seas. 1996. The efficacy of in-situ burning Alaskan oils. Report in progress to ADEC, Juneau, AK.

S.L. Ross Environmental Research Ltd. 1995. Demulsifiers and modified heli-torch fuels to enhance *in-situ* burning of emulsions. Report to ACS, Prudhoe Bay, AK.

S.L. Ross Environmental Research Ltd. 1994. Spill-related properties of fresh and weathered Alaskan crude oils. Report to Alaskan Clean Seas, Anchorage, Alaska.

Strøm-Kristiansen, T., A. Lewis, P. Daling and A. Nordvik. 1995. Demulsification by use of heat and emulsion breaker. Proceedings of the Eighteenth AMOP Technical Seminar. Environment Canada, Ottawa. pp. 367-384.

Zagorski, W. and D. Mackay. 1982. Water in oil emulsions: a stability hypothesis. Proceedings of the 5th Annual Arctic Marine Oilspill Program Technical Seminar. Environment Canada, Ottawa.