

# ENHANCING THE IN-SITU BURNING OF FIVE ALASKAN OILS AND EMULSIONS<sup>1</sup>

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**ABSTRACT:** A study of the efficacy of in-situ burning (ISB) as a response tool for oils transported in Alaska has been partially completed. The first phase of the work involved laboratory burn tests to determine, with four oils, the limits to ignition imposed by evaporation and emulsification. Tests were also conducted to determine the effectiveness of chemical emulsion breakers in extending the ignition limits. The results demonstrate that the combination of evaporation and emulsification can severely curtail the ignition of slicks of the oils, but that application of an emulsion breaker can significantly extend the window of opportunity for ISB. Both the limits to ignition and the effectiveness of the emulsion breaker addition were found to be dependent on the oil type; oil-specific testing is required to ascertain the potential effectiveness of ISB and emulsion breaker addition. The second phase of the study comprised a series of burn tests with Alaska North Slope (ANS) crude in waves. For untreated slicks, burn efficiency and burn time both decreased with increasing wave energy; burn rate and the amount of residue increased with increasing wave energy. These effects were most pronounced for the thicker slicks and heavily weathered oil and emulsion. The application of a commercially available emulsion breaker permitted the successful burning of otherwise unignitable ANS emulsion slicks in waves. The results showed that mixing energy, either from mechanical agitation or from wave action, was necessary for the emulsion breaker to be effective. The most significant result was the successful burning in waves of a weathered 60% water ANS emulsion following the addition of a 1:500 dose of emulsion breaker with mixing energy imparted to the slick only by wave action.

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, with the evaporation of an oil's light ends and the formation of a water-in-oil emulsion, the slick can quickly become unignitable and the "window-of-opportunity" for a successful in-situ burn can be closed. Recent tests in Alaska, which followed from studies in Norway and Canada, have demonstrated that applying chemical breakers to emulsions contained by fire-resistant booms has the potential for greatly extending the ISB window-of-opportunity. Previous laboratory tests, small-scale burns in pans, and mesoscale tests have proved that the addition of emulsion-breaking chemicals to certain oils can permit the successful ignition and burning of otherwise unignitable slicks. The operational approach envisioned is to (1) collect the emulsion with a "U" of fire boom towed through the slick; (2) move a safe distance crosswind from the main slick; (3) apply emulsion breakers aerially at low (about 1:500) dose rates to the entire surface of the contained emulsion; (4) allow the emulsion breakers to

work for a period of time (probably dependent on the oil type, the chemical, and the mixing environment; for some oils this time is zero and the chemical and igniter can be applied simultaneously); and (5) ignite the contained emulsion over a wide area using alternative, gelled fuels dropped from a Heli-torch.

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 reported 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. Beginning to understand the processes involved was one of the main goals of this work.

This study builds on a previous project (S.L. Ross, 1995) by testing the ignition and burning of different Alaskan oils (crudes and fuels) and applying previous burning techniques under more realistic environmental conditions, namely, colder temperatures and waves. To date, phases 1 and 2 of the study have been completed. Phase 1 comprised a comprehensive series of small-scale burn and emulsion-breaking tests with four oils transported in the state of Alaska. Phase 2 involved tests on the effects of waves on small-scale burns of Alaska North Slope (ANS) crude and its emulsions. The plan for phase 3, which has been delayed while additional funding partners are being sought, is to conduct midscale emulsion burn tests in a newly constructed wave tank at Alaska Clean Seas (ACS) this spring or next fall.

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

## Emulsion formation tendency and stability

The results from the emulsion tendency and stability testing for the four Alaskan oils are presented in a previous paper (Buist *et al.*, 1996). All the oils were found to have 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.

## Emulsion breaker effectiveness

The results from the emulsion breaker effectiveness tests are also given in the earlier paper. The results indicate that, overall, EXO-0894 was the most effective at breaking the emulsions.

1. 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.

### Baseline burns with no waves

Forty-two baseline burns were conducted to determine the limits to ignition and burning of 2-cm-thick slicks of the emulsified Alaskan oils. Tests were conducted in a 40-cm-diameter steel ring floated in the middle of a 11 m × 1.2 m × 1.2 m (L × H × W) wind-wave tank filled with water to a depth of 85 cm. The smoke from the burns was removed with a fume hood suspended 1.5 m above the steel ring. 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.

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

1. Preweighed amount of Heli-torch gelled igniter fuel (75% gasoline:25% fresh ANS crude)
2. 1-mm layer of fresh crude as primer
3. 2-mm layer of fresh crude as primer

Table 1 summarizes the results of these tests. Full data may be found in the previous paper. The fresh Drift River crude emulsion was ignitable, even with a 60% water content. The 24% volume evaporated crude had a maximum ignitable water content of 25% at 3°C, but the 60% water emulsion could be ignited at 15°C. Only 25% water emulsions of the 35% evaporated Drift River crude could be ignited.

The maximum ignitable water content of the fresh Endicott crude was 25% at 3°C but increased to 60% at 15°C. The evaporated Endicott crude was ignitable only up to 25% water. The fresh and 9% evaporated Pt. McIntyre crude had a maximum ignitable water content of 25% at both test temperatures. Only 12.5% water emulsions of the 18% evaporated Pt. McIntyre crude could be ignited. The IF-30 fuel oil had maximum ignitable water content of 25% at 3°C; although the same procedure was followed, the 25% fuel oil emulsion could not be ignited at 15°C.

### 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. A measured dose (5 mL or 1:500 demulsifier to emulsion) was added dropwise to the surface of the slick, then mixed gently with a small stir stick. The treated slick was then allowed to break for 45 minutes prior to ignition. For comparison, higher temperature burns were conducted with Alcolpol and EXO-0894 on Endicott emulsions and with Breaxit

and EXO-0894 on Pt. McIntyre emulsions. (The emulsion breaker effectiveness test indicated that better results were possible using Alcolpol with some Endicott emulsions and Breaxit with some Pt. McIntyre emulsions.) The full data sets for the emulsion breaker burns may be found in the previous paper (Buist *et al.*, 1996).

Table 2 summarizes the results of these tests. The addition of the emulsion breaker EXO-0894 increased the burnable water content from 25% to 60% for both evaporated Drift River crude oils at 3°C. With Endicott crude, the emulsion breaker increased the maximum ignitable water content from 25% to 60% for both the fresh and 9% evaporated oil. The Alcolpol emulsion breaker worked just as well with the Endicott. The emulsion breakers had no effect on the ignition of the 17% evaporated Endicott crude. 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 and effectively increase the available response time for ISB operations from less than a day to a week.

The emulsion breakers had little effect on the Pt. McIntyre crude, only increasing the ignition limit from 25% to 40% water for the fresh oil. It is possible that other emulsion breaker formulations or different dosages would result in better effectiveness with the Pt. McIntyre crude. The addition of the emulsion breaker enabled the ignition of the 40% water IF-30 emulsion. The 60% water emulsion was not stable and could not be tested.

### Burns in waves

The small-scale study of burning ANS oil and emulsions in waves was conducted in the same tank using the same basic procedures as outlined in text preceding, except that the wave generator was turned on immediately after the slick was fully on fire. The parameters that were varied during phase 2 were degree of evaporation, initial slick thickness, emulsion water content, and wave energy.

Three wave settings were used in phase 2: high energy, low energy, and calm (i.e., no waves). Water temperature was between 11°C and 14°C throughout the tests. Waves were produced at one end of the test tank with a paddle board powered by a variable speed electric motor. A wave absorber was located at the other end of the tank to dissipate wave energy and reduce wave reflection. The characteristics of the waves produced are given in Table 3. It is not possible to translate these to equivalent conditions at sea. Wave steepness (height/wavelength) was used to quantify the wave conditions, with a higher wave steepness

**Table 1. Baseline burn results**

Oil type	Evaporation (% volume)	Maximum ignitable H <sub>2</sub> O (% water in emulsion)
Drift River crude	Fresh 24%	60% @ 3°C
		25% @ 3°C
	35%	60% @ 15°C
		25% @ 3°C
Endicott crude	Fresh	25% @ 15°C
		25% @ 3°C
	9% and 17%	60% @ 15°C
		25% @ 3°C
Pt. McIntyre crude	Fresh	25% @ 15°C
		25% @ 3°C
	9%	25% @ 15°C
		25% @ 3°C
IF-30 fuel oil	18%	12.5% @ 3°C
		12.5% @ 15°C
	Fresh	25% @ 3°C
		<25% @ 15°C

**Table 2. Emulsion breaker burn results**

Oil type	Evaporation (% volume)	Increase in ignitable H <sub>2</sub> O (% water in emulsion)
Drift River crude	Fresh	Still 60% @ 3°C
	24%	From 25% to 60% @ 3°C
Endicott crude	35%	From 25% to 60% @ 3°C
	Fresh	From 25% to 60% @ 3°C
Pt. McIntyre crude	9%	From 25% to 60% @ 3°C
	17%	Still 25% @ 3° and 15°C
	Fresh	From 25% to 40% @ 3°C
	9%	Still 25% @ 3° and 15°C
IF-30 fuel oil	Fresh	From 12.5% to 25% @ 3°C
		From 12.5% to 25% @ 15°C
		From 25% to 40% @ 3°C (60% emulsion not stable)

Table 3. Wave properties

Property	Wave energy level		
	Calm	Low	High
Height (H, cm)	0	9 to 11	14 to 15
Period (s)	0	2	1.25
Wavelength ( $\lambda$ , cm)		3.3	2.0
Velocity ( $c$ , m/s)	0	1.2	1.7
Steepness ( $H/\lambda$ )	0	0.03	0.075
Energy <sub>2</sub> (E, J/m <sup>2</sup> )	0	122.5	183.8

1. Phase velocity:  $c^2 = g(1 - \rho_a/\rho_w)\tanh(\kappa h)/\kappa$

where:  $\rho_a$  = density of air (kg/m<sup>3</sup>)

$\rho_w$  = density of water (kg/m<sup>3</sup>)

$\kappa = 2\pi/\lambda$  (m<sup>-1</sup>)

$g$  = force of gravity (N/kg)

2. Energy:  $E = \rho_w g(H/2)^2/4$

corresponding to a higher wave energy. For each test the burn time, efficiency, rate, and amount of residue were plotted against wave steepness.

**Burns with water-free oil slicks in waves.** For 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 (see Figure 1B) decreased with increasing wave steepness; the effect was more pronounced as slick thickness increased. Burn efficiency (see Figure 1C) was little affected by waves; however, the amount of residue remaining after a burn (see Figure 1D) increased appreciably with increasing wave steepness. The increase in residue mass was only a small percent of the initial oil mass.

The results of the tests with the 10.3% evaporated ANS are shown in Figure 2. The burn rate (see Figure 2A) remained fairly constant with increasing wave steepness for the 5-, 10-, and 20-mm slicks. For the 2-mm-thick slick, the trend is not clear because of scatter, although the high wave energy did produce a sharp decrease in burn rate. Burn time (see Figure 2B) was not affected by increasing wave steepness for all slick thicknesses. The burn efficiency results (see Figure 2C) were difficult to interpret; the efficiency for the 5- and 10-mm slicks showed a slight decrease with increasing wave steepness. For the 2-mm slicks, the efficiency increased from calm to low wave energy, then sharply decreased at high wave energy. This may represent the approach of a limit to burning of this thickness and degree of weathering. The opposite occurred with the 20-mm slicks: efficiency decreased from calm to low wave energy and then increased at high wave energy. The amount of residue remaining after a burn was almost constant for the 2-, 5-, and 10-mm burns, but increased substantially for the 20-mm slick at low wave energy.

For burns using 15% weathered ANS crude, the burn rate (Figure 3A) generally increased with increasing wave steepness (2-mm slicks were not tested since they were found to be unignitable). Burn time (see Figure 3B) was not appreciably affected by wave steepness for the 5-mm slicks, and was 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 (see Figure 3C) appeared to be one of decreasing efficiency with increasing steepness. 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 26.6% weathered ANS crude (again, 2-mm slicks were not tested), the burn rate (Figure 4A) increased 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 for high-energy waves. This may represent the approach of a limit to burning of this thickness and degree of weathering, or it may

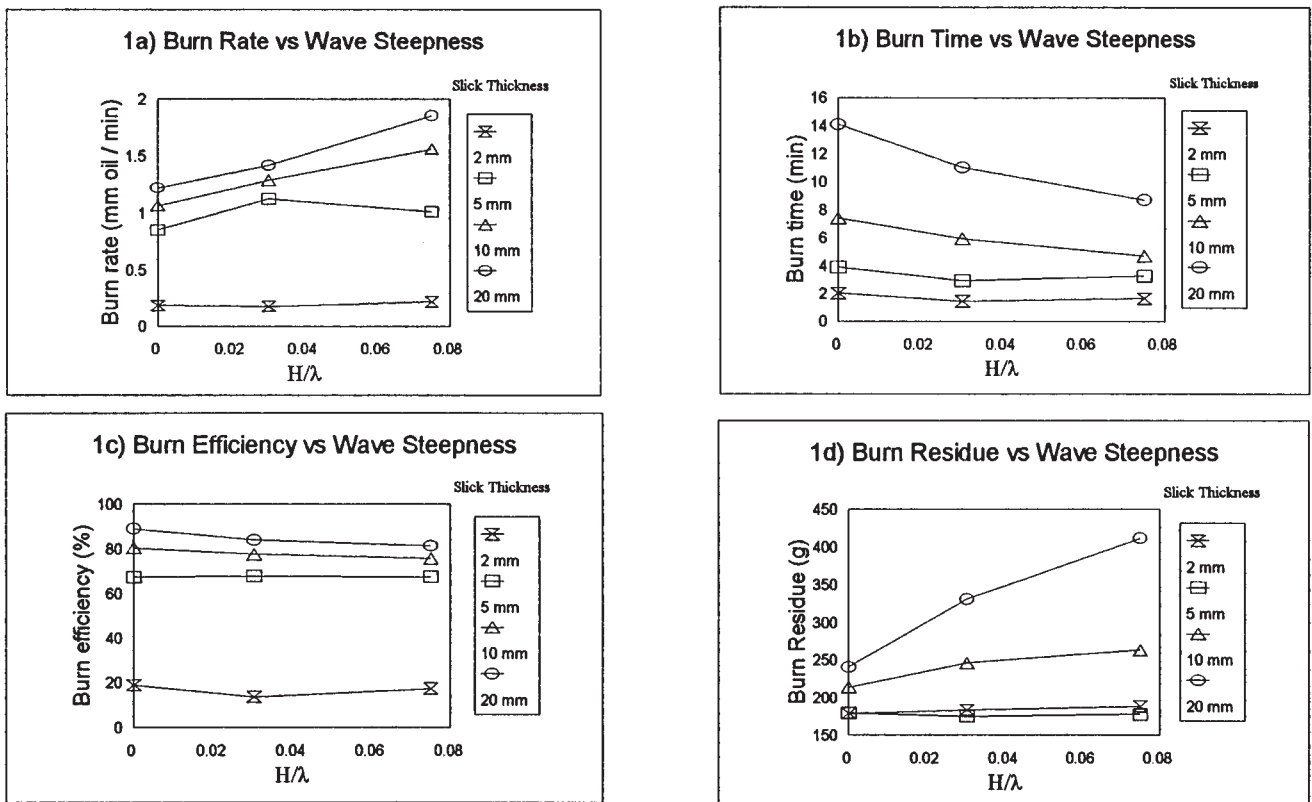


Figure 1. Fresh ANS burns in waves

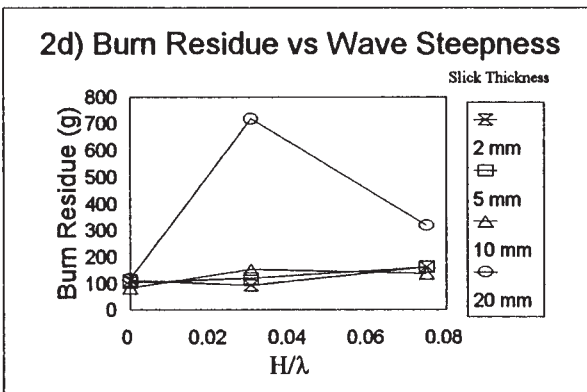
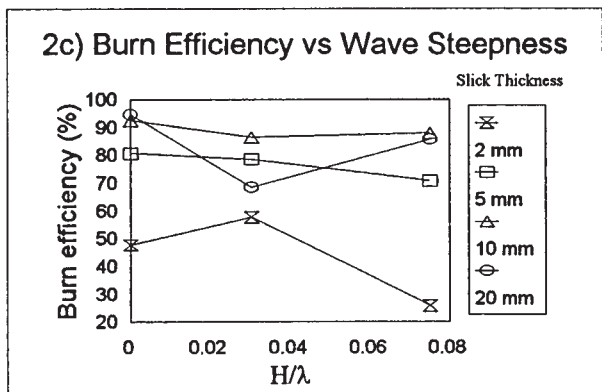
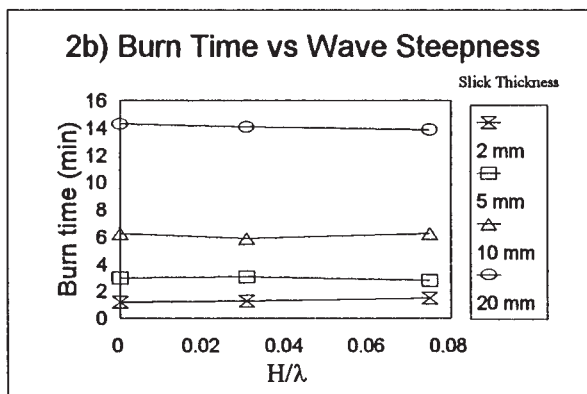
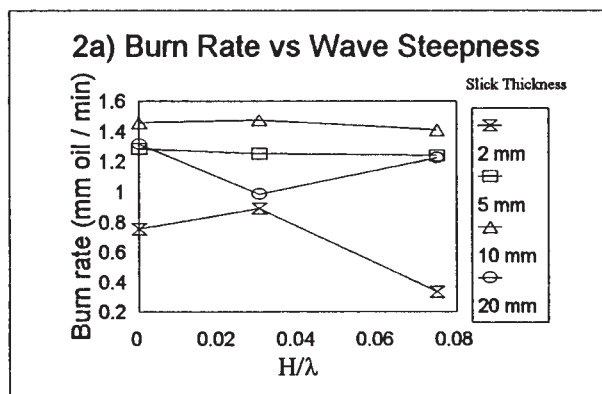


Figure 2. 10.3% evaporated ANS burns in waves

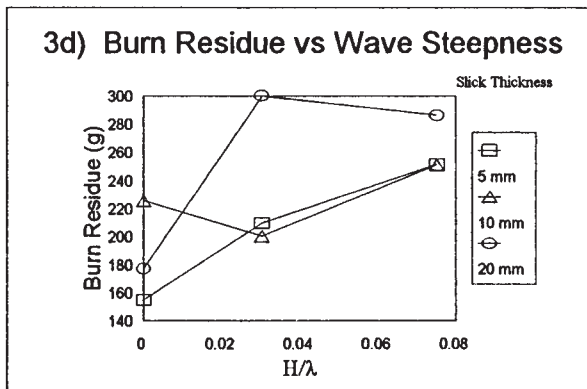
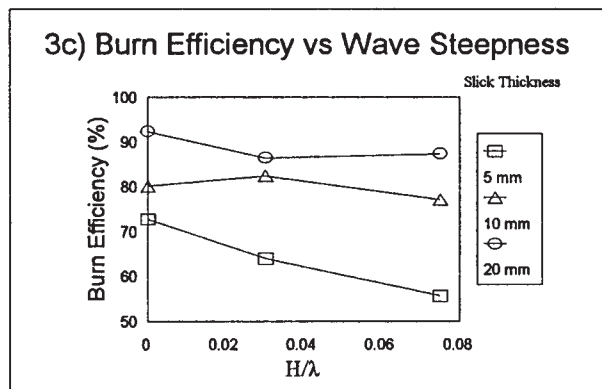
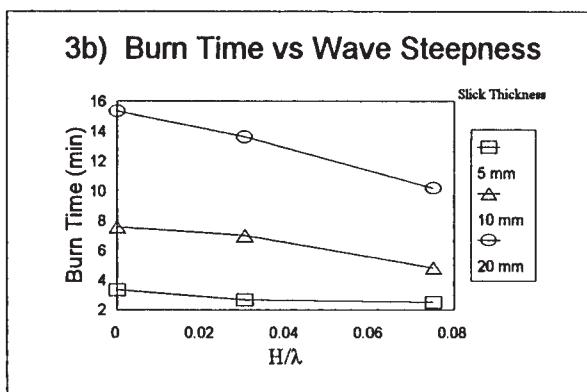
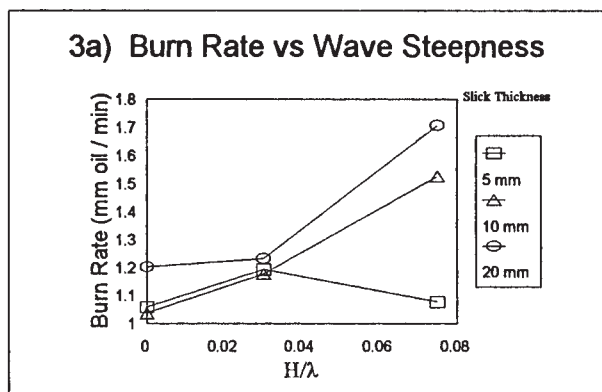


Figure 3. 15% evaporated ANS burns in waves

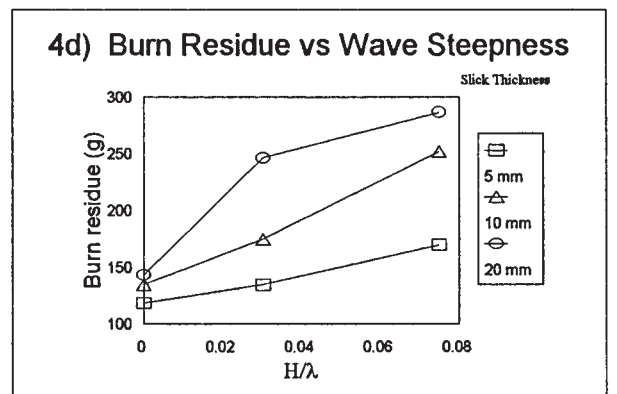
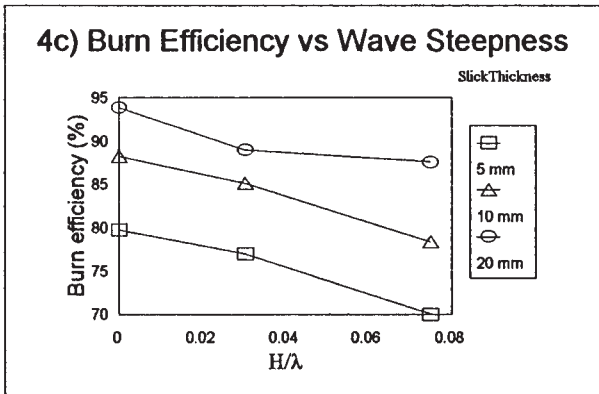
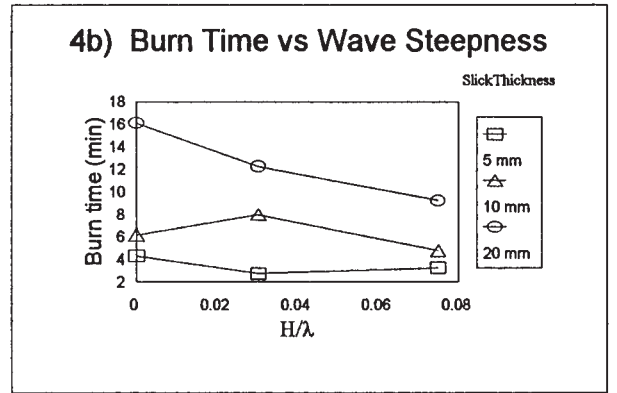
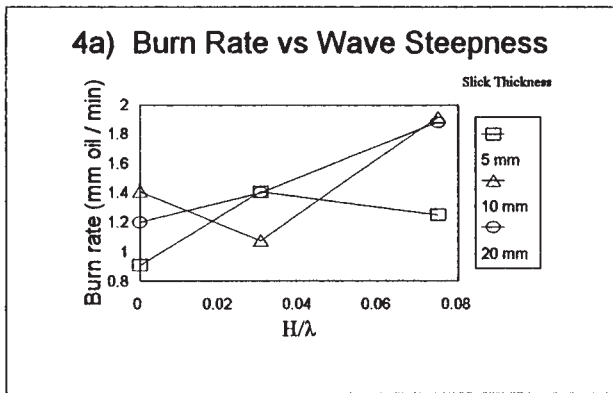
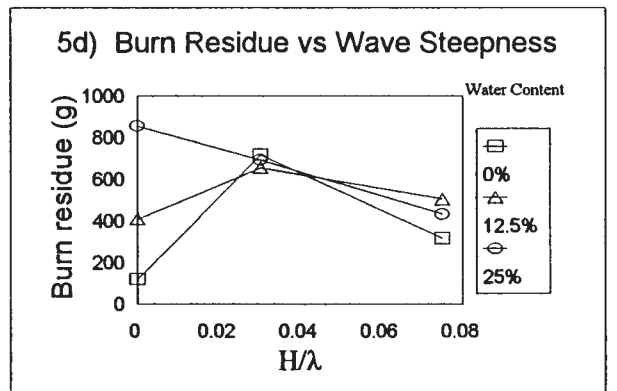
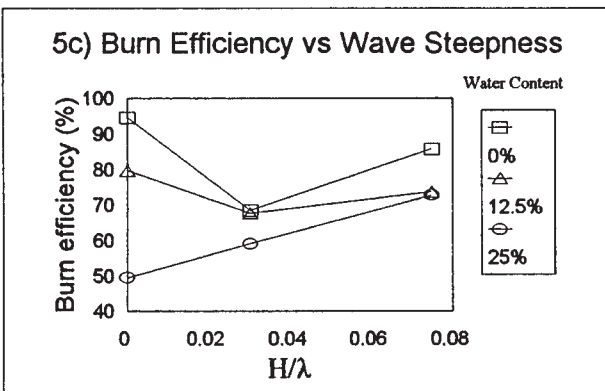
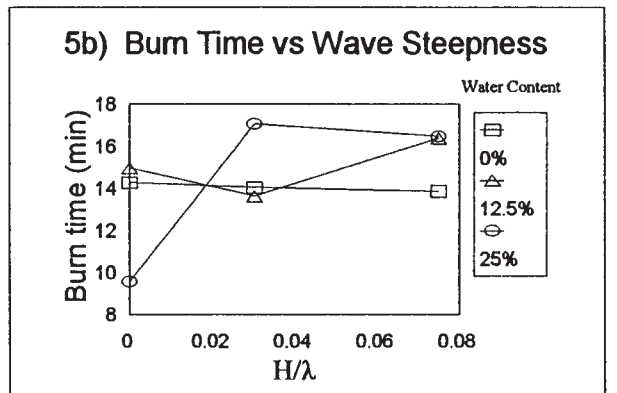
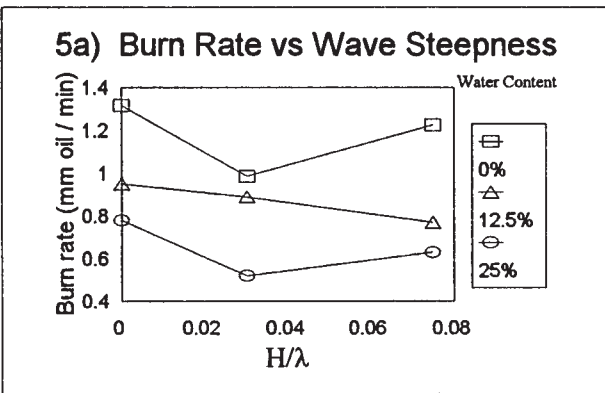


Figure 4. 26.6% evaporated ANS burns in waves



\* 40% water content unignitable

Figure 5. 10.3% evaporated ANS emulsion burns in waves (20-mm slicks)



be as a result of experimental error. The burn times (see Figure 4B) 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 (see Figure 4C) decreased with increasing wave steepness for all slick thicknesses. Likewise, the amount of burn residue remaining (Figure 4d) increased with increasing wave energy.

**Effects of waves on the burning of emulsified ANS crude.** A total of 19 burns were performed to investigate the effects of waves on the burning of emulsified slicks. The parameters varied included degree of weathering, emulsion water content, and wave energy. A slick thickness of 20 mm and a water temperature of 3°C were used for all burns. For both weathered oils, water content was increased in a stepwise manner until the emulsion was deemed unignitable.

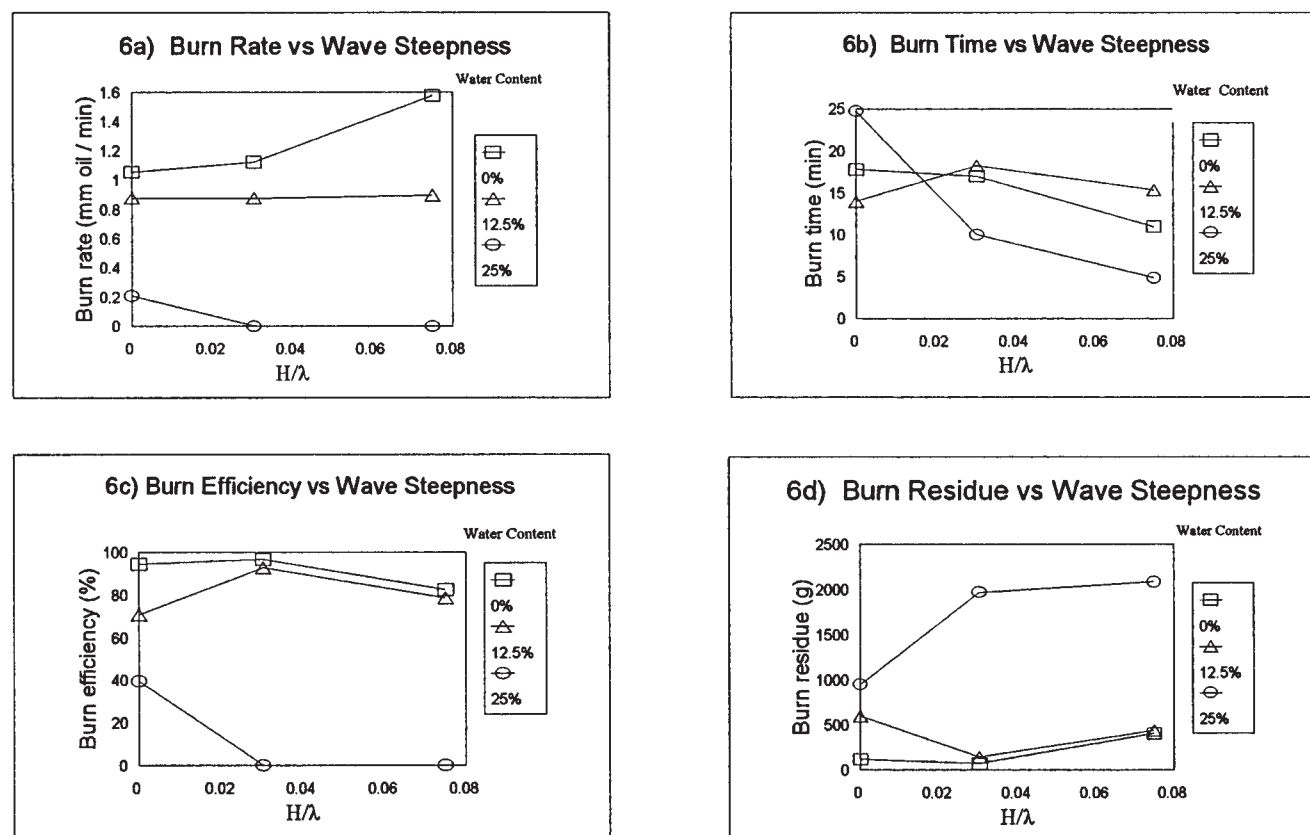
The results of the wave burn tests for the 10.3% evaporated emulsified ANS at various water contents are shown in Figure 5. The oil burn rate (see Figure 5A) decreased with increasing wave steepness for the water-free, the 12.5%, and the 25% water slicks. Burn time (see Figure 5B) remained relatively constant for the water-free and 12.5% water emulsion slicks; a sharp increase in burn time from calm to low waves was observed for the 25% water content emulsions. The burn efficiency (see Figure 5C) results were scattered and difficult to interpret; the 25% water content emulsion did show a steady increase in burn efficiency with increasing wave energy. A similar and related trend can be seen in the amount of residue remaining (see Figure 5D).

The results of the burn tests in waves with emulsions of 29.1% evaporated ANS of various water contents are shown in Figure 6. The oil burn rate (see Figure 6A) for the water-free oil increased with increasing wave steepness, showed no change for the 12.5% water content, and was zero in waves for the 25% water content (indicative of a successful ignition, but a very poor burn). Burn time (see Figure 6B) decreased slightly with increasing wave steepness for the water-free slicks and

remained relatively constant for the 12.5% water emulsion slicks; decreases in burn times with increasing wave steepness were measured for the 25% water content emulsions. The burn efficiency (see Figure 6C) was slightly reduced by waves in the case of the water-free oil and increased for the 12.5% water content emulsion. An efficiency of zero was found in waves for the 25% water content emulsion. A similar trend can be seen in the amount of residue remaining (see Figure 6D).

**Emulsion breaker burns in waves.** This task evaluated the ability of the chemical emulsion breaker EXO 0894 to extend the ignitability of the ANS emulsions in wave conditions. The tests involved spraying emulsion breaker onto otherwise unignitable emulsions of ANS crude and then igniting them with conventional or alternative gelled fuels. Both manual and wave-induced mixing of the chemical into the emulsion were tested. In both cases, chemical application was followed by a settling time of 45 minutes at the desired wave setting. A slick thickness of 20 mm and a water temperature of 3°C was used for all burns. A total of 21 emulsion breaker burns were performed.

Figure 7 shows burn test results when the emulsion breaker was manually mixed with the 10.3% evaporated emulsified ANS at 40% and 60% water content. Manual mixing of EXO 0894 into the emulsion was successful in promoting the ignition of both the 40% and 60% water content emulsions, which were otherwise unignitable, under all wave conditions. The 40% water content emulsion showed positive results as burn rate (see Figure 7A) steadily increased with increasing wave steepness. The burn rate of the 60% water content emulsion was the same at the calm and high wave settings (approximately 0.6 mm oil per mm), but was inexplicably zero at the low wave setting (indicating a poor burn). Burn times (see Figure 7B) decreased substantially with increasing wave steepness for the 40% water content but remained fairly constant for the 60% water content. Burn efficiency (see Figure 7C) and burn residue (see Figure 7D) remained constant for the 40% water content, but, for the 60% water content, burn efficiency sharply decreased



\* 25% water content unignitable in waves

Figure 6. 29.1%\* evaporated ANS emulsion burns in waves (20-mm slicks)

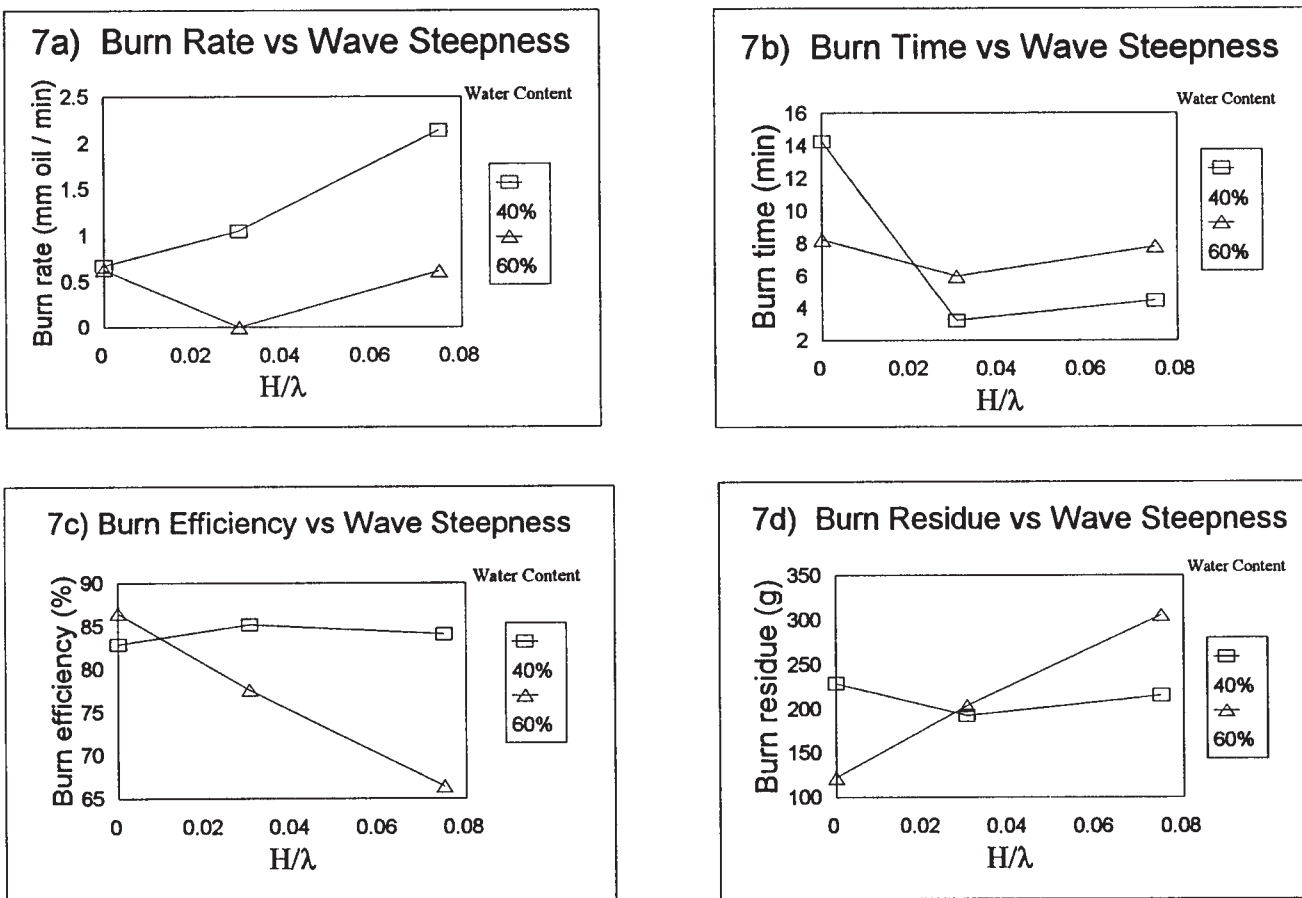


Figure 7. 10.3% evaporated ANS in waves with emulsion breaker manually mixed (20-mm slicks)

and the mass of burn residue sharply increased with increasing wave steepness.

Figure 8 shows the results for the same emulsions with only wave energy to mix the emulsion breaker. The burn rate (see Figure 8A) was zero in calm conditions (demonstrating the need for energy to mix the emulsion breaker). In waves the results were better, though not as good as those achieved with manual mixing. Burn efficiency (see Figure 8C) was also zero under calm conditions and increased with increasing wave steepness. The results for the 60% water content burn in low waves were nearly identical to those obtained with manual mixing. The 60% water content emulsion burns in high waves were inconclusive since, under these conditions, the emulsion could not be retained within the burn ring. Rather, it tended to disperse into the water column.

Figure 9 shows the results for manually mixed emulsion breaker with the most highly weathered ANS emulsions. Manual mixing of EXO 0894 into the emulsion was successful in promoting the ignition of the 25% water content emulsions under calm and low wave conditions, but not under high wave conditions. The 40% water content emulsion could just barely be ignited in calm and low wave conditions, and burned poorly. The 60% water content emulsion was found to be unignitable for all wave conditions. It seems that a 25% water content emulsion may be at the limit of the effectiveness of EXO 0894 under wave conditions for the 29.1% weathered oil. Wave-induced mixing of the emulsion breaker was also attempted with the 29.1% weathered oil, but it dispersed into the water column before ignition could be attempted.

## Discussion and summary

As expected, the ignition and burning of all four oils selected for phase 1 of this study were 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 with a stir stick, 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, semisolid emulsions. It should also be kept in mind that the emulsions used in these experiments were intentionally created to be very stable.

The second possible reason for the ineffectiveness of the breaker on the four oils in the first part of the study was that the tests were performed in quiescent conditions. The presence of wave action following emulsion breaker application will enhance mixing of the chemical and emulsion and thus accelerate the breaking process, as shown with ANS crude in the second part of the study. Static tests may not be the ideal measure of the efficacy of emulsion breaker addition in improving the in-situ burning of emulsions.

In-situ burning of the emulsions was also sensitive to ambient temperature. Generally, as temperatures increased, ignition of emulsions

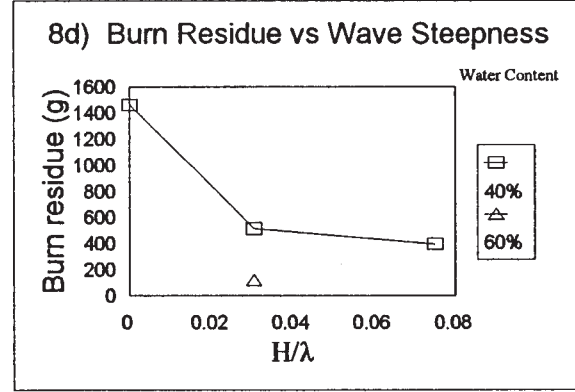
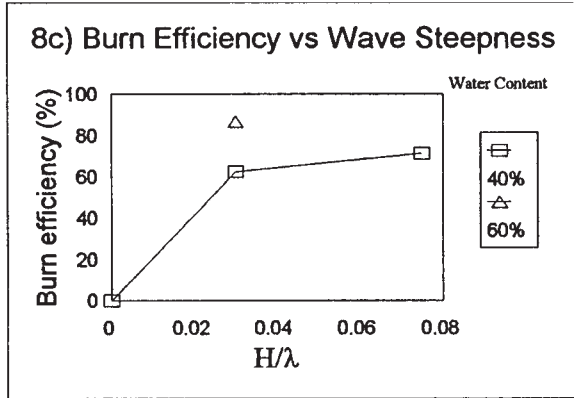
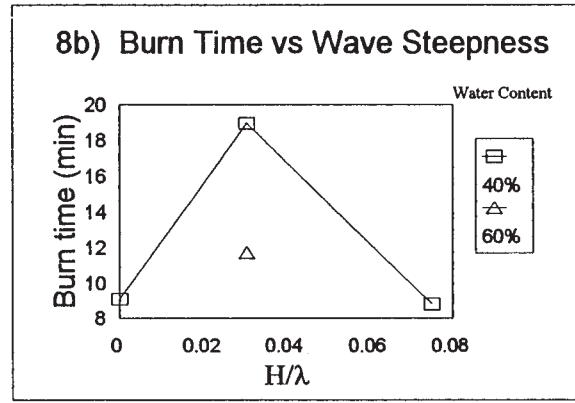
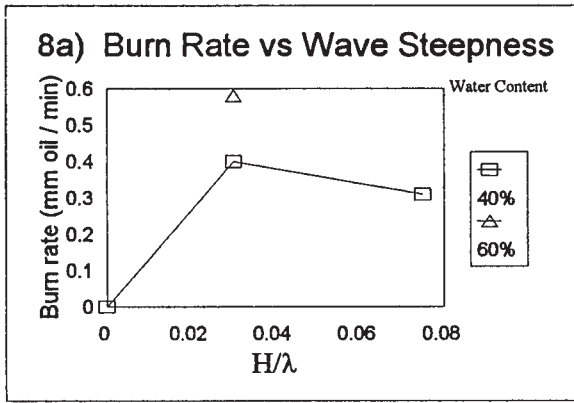


Figure 8. 10.3% evaporated ANS in waves with emulsion breaker naturally mixed (20-mm slicks)

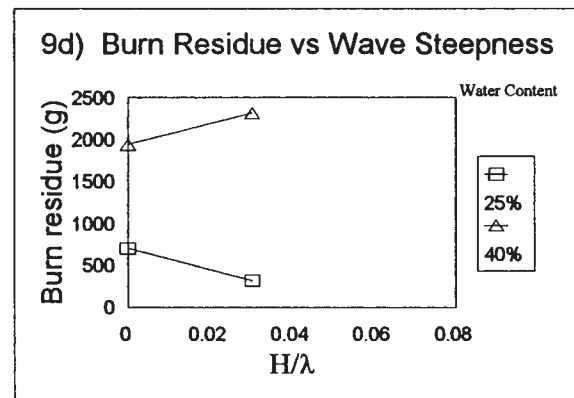
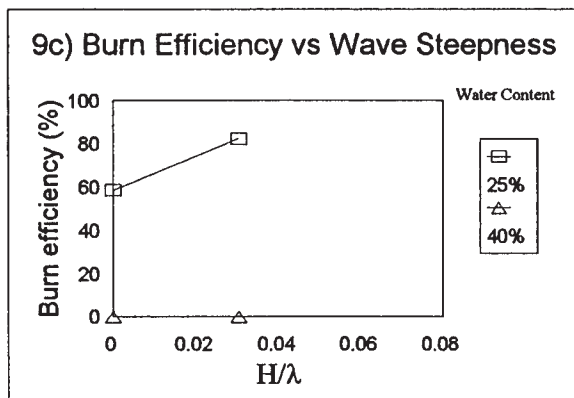
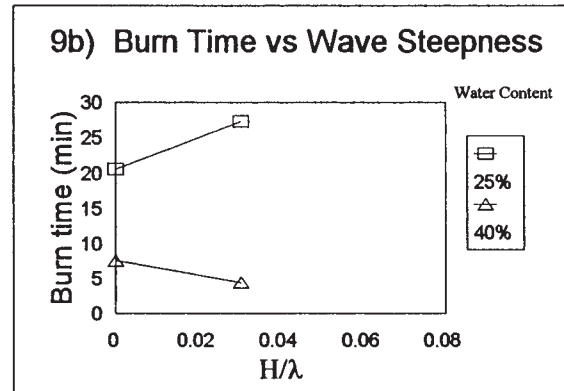
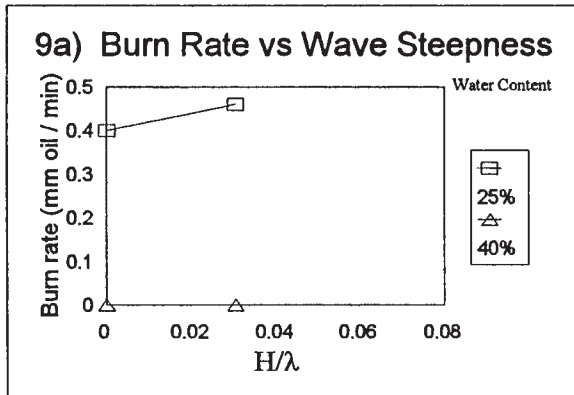


Figure 9. 29.1% evaporated ANS in waves with emulsion breaker manually mixed (20-mm slicks)



became easier and burn efficiency increased. This effect appears to be oil-specific, since 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.

The results indicate that, for unemulsified oils, increases in wave energy tended to increase the burn rate of thicker slicks (10 to 20 mm) of fresh and weathered ANS, but generally had little effect on the burn rate of the thinner slicks (2 to 5 mm). This trend may be related to an increase in heat transfer through the slick caused by wave action, which results in an increase in the burn rate. It may also be a result of wave-induced mixing of fresh oil up to the surface of the slick. Burn times generally decreased and the mass of burn residue amounts generally increased with increasing wave steepness for all slick thicknesses and degrees of evaporation. These results may relate to enhanced heat transfer through the slick caused by wave action, resulting in more rapid cooling of the slick and 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; the result would be quicker extinction. Finally, burn efficiency appears to be reduced (i.e., the amount of residue remaining increased) by wave action. This effect appears to be magnified by increasing levels of evaporation.

For ignitable emulsions of 10.3% and 29.1% evaporated ANS crude, increases in wave energy tended to decrease the burn rate of the 10.3% evaporated emulsions and had little effect on burn rate for the 29.1% evaporated emulsions. Increases in wave steepness did not significantly affect burn rate for low-water-content emulsions (12.5%) but tended to decrease burn rate for the higher-water-content (25%) emulsions, with the effect being more pronounced at higher degrees of weathering. Also, for both the 10.3% and 29.1% evaporated oils, the burn rate decreased steadily with increasing water content at constant wave steepness. This may be related to an increase in heat transfer through the slick caused by the increase in water content. Burn times, burn efficiency, and burn residue amounts were difficult to correlate.

For the emulsion breaker burns of unignitable emulsified oils of 10.3% and 29.1% evaporated ANS, the addition of EXO 0894 was successful in promoting the ignition of emulsions in wave conditions. Manual mixing of the emulsion breaker chemical was found to be somewhat more effective than mixing of the emulsion breaker with wave action alone. The results indicate that mixing energy supplied, either manually or by the waves, is necessary for the emulsion breaker to work. For the 10.3% evaporated ANS, both the 40% and 60% water content emulsions burned successfully in waves. It is extremely encouraging that the 60% water content emulsion of 10.3% weathered ANS was successfully ignited and burned in waves with the addition of a chemical emulsion breaker. The addition of EXO 0894 to the 29.1% evaporated ANS emulsions was not very effective in extending the ignition limits.

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## Biography

Ian Buist is one of Canada's leading experts on oil spill behavior and countermeasures and is an acknowledged worldwide authority on in-situ burning with over 17 years experience. He is senior engineer and vice president with S.L. Ross Environmental Research Ltd. in Ottawa. At present he is quantifying the in-situ burning potential for Alaskan oils and the effects of waves on burning for ADEC and ACS; testing six other U.S. OCS crude oils for burnability (including soot production) and conducting an in-depth literature review of smoke yields from in-situ burns for MMS; reviewing the application of in-situ burning in Prince William Sound for the PWSRCAC; and developing a large-scale test in waves for fire-resistant booms using propane flames for MMS.

## References

1. 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*. Environment Canada, Ottawa, pp735-748
2. Buist, I., J. McCourt, K. Karunakaran *et al.*, 1996. *In-situ* burning of Alaskan oils and emulsions: Preliminary results of laboratory tests with and without waves. *Proceedings of the 19th AMOP Technical Seminar*. Environment Canada, Ottawa, pp1033-1062
3. 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 6th AMOP Technical Seminar*. Environment Canada, Ottawa, pp70-84
4. Fingas, M. F., G. Halley, F. Ackerman *et al.*, 1995. The Newfoundland offshore burn experiment-NOBE. *Proceedings of the 1995 Oil Spill Conference*. American Petroleum Institute, Washington, D.C., pp123-138
5. Ross, S. and I. Buist, 1995. Preliminary laboratory study to determine the effect of emulsification on oil spill evaporation. *Proceedings of the 18th AMOP Technical Seminar*. Environment Canada, Ottawa, pp91-110
6. S. L. Ross Environmental Research Ltd., 1995. Demulsifiers and modified Heli-torch fuels to enhance *in-situ* burning of emulsions. Report to Alaska Clean Seas, Prudhoe Bay, Alaska