Mid-Scale Tests of *In Situ* Burning in a New Wave Tank at Prudhoe Bay, AK

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Abstract

A series of research burns was carried out in the fall of 1997 in Prudhoe Bay, AK in a new wave tank purpose-built for *in situ* burning studies. These tests were the culmination of a three-year research project by Alaska Clean Seas (ACS) and SL Ross into the effects of oil type, emulsification, temperature and waves on *in situ* burning in Arctic open water conditions. The experimental program involved conducting mid-scale (1.7 m diameter) burns with fresh and weathered Alaska North Slope (ANS) and Milne Pt. crude oils and emulsion slicks in waves. Over 60 individual burns were conducted varying slick thickness, water content, wave energy, degree of weathering and oil type. In addition to the valuable data on the scaling of *in situ* burning processes in waves, perhaps the most significant operational result was that it was possible to burn 60% water content emulsions of heavily weathered ANS crude in the highest wave conditions tested (23 cm high waves with a length of 4.7 m and a period of 2 seconds) with the addition of emulsion breakers. The 60% water emulsion of the weathered Milne Pt. crude was burnable in these waves without emulsion breaker addition.

1.0 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 the formation of a water-in-oil emulsion 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 by fire resistant booms. Previous laboratory tests, small-scale burns in pans, and meso-scale tests (e.g. SL Ross, 1995; Guénette *et al.*, 1994 and 1995) 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: i) collect emulsion with a "U" of fire boom towed through the slick; ii) move a safe distance crosswind from the main slick; iii) apply emulsion breakers aerially at low (ca. 1:500) dose rates to the entire surface of the contained emulsion; iv) allow the emulsion breakers to work for a period of time; and, v) ignite the contained emulsion over a wide area using alternative, gelled fuels dropped from a Heli-torch. The waiting period between breaker application and ignition is probably dependant on the oil type, chemical and mixing environment - for some oils this time is zero and the emulsion breaker and igniter can be applied simultaneously.

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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 mid-scale test had 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.

Beginning to understand the processes involved with burning in waves was one of the main goals of this work. This study built on a previous project that investigated the *in situ* burning of ANS crude and emulsions in calm conditions at scales up to 9 m (SL Ross, 1995). The present study continued this research by testing the ignition and burning of different Alaskan oils (crudes and fuels) and applying burning techniques under more realistic environmental conditions, namely colder temperatures and waves. The objective of this research program was to determine the effective limitations that oil properties (% emulsification and viscosity) and physical environmental conditions (temperature and waves) place on the *in situ* burning of Alaskan risk oils.

Previous papers in 1996 (Buist *et al.*, 1996) and 1997 (Buist *et al.*, 1997) have described the lab-scale tests that comprised the first two phases of the present study. This paper describes the final phase, a series of mid-scale research burns carried out in the fall of 1997 in Prudhoe Bay, AK.

The goals of the mid-scale burn test phase of the study were to:

i) design and fabricate a suitable wave tank for outdoor *in situ* burning tests at Prudhoe Bay; and,
ii) perform mid-scale outdoor research burns with weathered ANS and Milne Pt. crude oils and emulsions in the wave tank, including the application of emulsion breakers.

2.0 Test Equipment and Procedures

2.1 Wave Tank

A custom tank was commissioned for this project. It is of all-steel construction and was designed to be road-transportable. The general layout is shown in Figure 1 and the tank, photographed at the ARCO Fire Training Ground in Prudhoe Bay where the tests were conducted, is shown in Figure 2. The inside dimensions of the tank are: 12 m long x 2.4 m wide x 2.25 m high (40 ft x 8 ft x 7.4 ft). The tank was fitted with a simple, hydraulically-driven wave paddle at one end (Figure 3) and passive wave absorbers (Figure 4). The wave absorbers consist of sheets of perforated metal inserted vertically at both ends of the tank. These metal sheets have differing degrees of permeability specifically designed to damp incoming waves. The bundle of wave absorber panels at the end of the tank opposite the wave paddle also had horizontal perforated metal sheets placed over them (Figure 4). Complete design drawings of the tank and absorber panels may be found in the project report (SL Ross, 1998).

An iron pipe with holes drilled in it every few centimetres was suspended along each side of the tank to spray water against the inside surface of the exposed wave tank wall to make certain the tank wall did not buckle when exposed to heat from the test fires. The cooling water was pumped from one of the discharge valves on the "beach" end of the tank itself to prevent water depth changes

The wave paddle was controlled by a simple electronic sine wave function generator system that regulated the flow of hydraulic fluid from the power pack to the cylinder. The frequency and amplitude of the movement of the cylinder (and thus the wave paddle) could be independently controlled from a panel mounted on the side of the tank (Figure 5). The hydraulic fluid for the wave paddle system was supplied at 2500 psig from a Hyde Products diesel-driven power pack.

With 1.8 m (72 inches) of brackish water taken from Prudhoe Bay (with a density of 1.007 g/mL equivalent to a salinity of approximately 10 ppt) in the tank, the wave maker was capable of generating waves with heights of more than 45 cm (18") and periods ranging from 1.7 to 3.3 seconds. The corresponding wavelengths were 4.2 m to 12 m (14 ft to 40 ft). Smaller waves and shorter wavelengths, for example a 26 cm (10 inch) wave with a period of 1.3 s and a length of 2.6 m, (8.5 ft), were also possible. The wave absorber design completely eliminated any reflected waves from the ends of the tank.

Table 1 shows the characteristics of the waves generated in the tank at various settings of the frequency and amplitude potentiometers on the control panel. The settings chosen for the "low" (steepness ratio of 0.03) and "high" (steepness ratio of 0.05) energy waves for the burn tests are highlighted. For the first tests with the "high" energy waves, a steepness ratio of 0.065 was used. This wave energy caused a standing circular wave to set up inside the containment boom. At the centre of the circle of the boom, where the standing wave converged, the wave energy highly disturbed the test slick and may have dispersed it into the water column. A lower wave steepness (0.05) was selected for all subsequent "high" wave energy tests.

A 6 m (20 ft) section of old Shell fire boom was formed into a 1.7 m (5' 4") inside diameter circle for use as a burn ring. The enclosed area was approximately 2.1 m^2 (22.5 ft^2). The burn ring was held loosely in the center of the wave tank by wires attached to the sides. Sufficient play was left in the attachment wires to allow the ring to move up and down with the waves. As well, in order to facilitate filling the ring with oil, applying igniters and recovering residue, the ring was held loosely enough to allow it to be moved to one side of the tank or the other.

2.2 Experimental Methods

2.2.1 Oil Samples and Evaporation

Two crude oils were tested: ANS crude and Milne Pt. crude. In total, 1.2 m^3 (7.6 bbls) of ANS crude were obtained from Pump Station #1on the Trans-Alaska Pipeline; and, 1.3 m^3 (8.3 bbls) of Milne Pt. crude were obtained from from well MPU C-23. Of the ANS crude obtained, 410 L (2.6 bbls) was set aside to be used fresh (330 L for burn tests and 75 L for gelled fuel preparation). The remainder (800 L) was artificially evaporated. For the Milne Pt. crude, 330 L was set aside to be used fresh in burn tests and the remainder (980 L) was artificially evaporated.

The required volume of fresh oil was placed in a tank and compressed air bubbled through it until it has lost the desired percent of its initial volume (20% loss for the ANS crude and 30% loss for the Milne Pt. crude). At the same time the oil was recirculated through a spray nozzle that atomized the oil to increase its area in contact with the air. The oil droplets were sprayed against a plastic curtain that directed them back into the weathering tank. After several days of bubbling and spraying, steam coils were placed in the tank to accelerate the evaporation rate by heating. The ANS crude was weathered first, followed by the Milne Pt. crude. The weathered crudes were placed in separate, sealed containers until required for the experiments.

2.2.2 Emulsion Preparation

Some of the tests involved the use of emulsified oil. The emulsions were prepared just prior to the tests, to ensure good consistency and high stability. This involved mixing various volumes of seawater with the weathered crude oil using an air-powered gear pump. The procedures are detailed in the project report (SL Ross, 1998). For each test a volume of 63 L (16.6 gallons) of emulsion was required. In total, 820 L (135 gallons) of seawater were required to produce the emulsions. It was discovered that the seawater taken from Prudhoe Bay had a density of only 1.007 g/mL, equivalent to a salinity of only 10 ppt, as opposed to normal seawater with a salinity of 35 ppt and a density of 1.025 g/mL. As such, the emulsions created initially with the 10 ppt Bay water were not fully stable, and for most of the emulsion burn tests table salt was added to the water used to prepare the emulsions to bring its density up to 1.025 g/mL.

2.2.3 Gelled Fuel Preparation

Two types of gelled fuel igniterswere required for the tests: gelled gasoline and a gelled mixture of 75% gasoline with 25% fresh ANS crude. The latter was used ti ignite the emulsions. The detailed procedures used to prepare these igniters are given in the project report (SL Ross, 1998).

2.2.4 Unemulsified Oil Burn Tests

The test matrix called for 36 test burns with unemulsified oil. This matrix varied wave steepness (calm, low and high), oil slick thickness (5, 10 and 20 mm) and degree of evaporation (fresh and evaporated) for the two test oils (ANS and Milne Pt. crudes). The procedures for each unemulsified oil burn test were as follows.

After the appropriate volume of oil was measured out and the weight of oil recorded , it was transferred into the burn ring. The oil was added via a spill plate that consisted of a steel funnel welded to a steel downspout with a horizontal plate welded on the outlet at the water level. This prevented the oil from submerging beneath the boom as it was being added. The volume of oil used for each test varied with the desired slick thickness.

After the oil had been added to the ring, and the ring re-positioned in the center of the wave tank, the wind speed was recorded using both a hand-held anemometer (at a height of about 25 cm above the surface of the oil in the burn ring) and a portable weather station mounted nearby. The cup of the anemometer of the weather station was 6.3 m (20' 10") above ground level. The temperature of the air and water was also recorded. The detailed weather records for the test period (August 23 to September3, 1997) were obtained from nearby weather stations.

For the unemulsified oil burn tests, a baggie containing 120 mL (4 fluid ounces) of gelled gasoline was used to ignite the slicks. These gelled fuel bags were placed on the oil then ignited with a propane torch taped to a pole (Figure 6). Once the flames had spread to cover the entire surface of the slick, the waves were turned on at the desired settings given in Table 1.

For each burn test the following were recorded:

- preheat time - the time from firing the igniters until flames began to spread away from the burning gelled fuel and reached an area of approximately 1 m^2 (10 ft^2);
- ignition time - the time from firing the igniters until the flames covered the entire ring surface;
- vigorous burn time - the time from firing the igniter until the water beneath the slick began to boil causing higher flames, greater flame radiation, oil droplets to be sprayed up from the slick and/or a hissing sound; and,
- extinction time - the time from firing the igniters until the flames completely extinguish.

For some of the slower burns, the following were also recorded, in order to more accurately calculate burn rates:

- the time for the flames to spread to cover 25%, 50% and 75% of the slick surface during ignition; and,
- the time for the flames to recede to 50% of the slick surface during extinction.

Each burn was videotaped, photographed and observed visually from a person-basket elevated by a front-end loader located off the "beach" end of the tank so as to look down the tank towards the wave paddle. A typical burn is shown in Figure 7.

After each burn, the residue was allowed to cool. The residue was then collected with shovels, pitchforks and pre-weighed sorbents. The residue and sorbents were placed in pre-weighed plastic bags. The bags were then weighed and the mass of the residue determined to allow calculations of burn efficiency and rate. The burn efficiency was calculated by comparing the weight of the residue with the weight of oil added initially as given by equation 1 below. The burn rate was calculated by dividing the volume of oil burned by the area of the ring on fire as a function of time, as given by equation 2 below.

$$\text{Burn Efficiency (\%)} = \frac{(\text{Initial Oil Mass} - \text{Residue Mass}) \times 100}{\text{Initial Oil Mass}} \qquad (1)$$

$$\text{Oil Burn Rate (mm/min)} = \frac{(\text{Initial Oil Mass} - \text{Residue Mass})}{(\text{Density of oil})(\text{Burn Area})(\text{Burn Time})} \qquad (2)$$

The burn time was defined as the difference between the extinction and ignition times recorded plus ½ of the difference between the ignition and preheat times. This latter time was added to account for the potentially significant amount of oil burned as the flames spread to cover the entire surface area of the slick. If a particular burn involved a long extinction phase, where the flames slowly shrank to extinction rather than going out relatively quickly, the burn time was defined as the difference between the time for the flames to die back to cover 50% of the slick area plus ½ of the difference between the ignition and preheat times. This modification accounts for the potentially significant amounts of oil burned as the flames slowly died out. Once the residue was recovered, the oil for the next burn was added to the ring and the process repeated. The ANS crude was tested first.

2.2.5 Emulsified Oil Burn Tests

A total of 18 emulsion burns were planned, nine for each oil, varying wave steepness (calm, low and high) and water content (25%, 50% and 60%). The slick thickness was held constant at 20 mm and only stable emulsions created with the evaporated oils were tested. In addition to the procedures detailed above for the oil burns, the following steps were required for the emulsion burns. The first ignition attempt was with a baggie of gelled gasoline. If this failed to ignite the emulsion, a baggie of gelled 75% gasoline/25% fresh crude was used. If this failed 4 baggies of the 75/25 gelled fuel were used. If this failed a hand-held igniter was used. If this also failed, 4 L (1 gallon) of 75/25 gelled fuel was to be spread over the surface of the oil and ignited. If this failed as well, 8 L (2 gallons) of fresh crude were to be spread over the surface of the slick and ignited with a baggie of gelled gasoline. If this failed the emulsion, and all higher water content emulsions were deemed unburnable without chemical enhancement and were treated with emulsion breakers.

Emulsion breaker treatment of an unburnable slick involved spraying the slick with 120 mL (4 fluid ounces - a dose rate of 1:500 breaker to emulsion by volume) of the appropriate emulsion breaker (EXO 0894 for ANS emulsions or Alcopol 0 70% PG for Milne Pt. emulsions). A hand-held domestic cleanser spray bottle was used for this purpose. If the test was to be conducted in calm conditions the breaker was manually mixed with the slick for a period of five minutes using a canoe paddle. Then the slick was left to sit for an additional 45 minutes. If the test matrix called for waves, the breaker was applied, then the waves were turned on at the low setting for 45 minutes. It was found that considerable oil was lost from the burn ring during the 45-minute settling period when the high wave setting was used.

At the end of the 45 minutes, the initial ignition attempt sequence involved: 4 baggies of the 75/25 gelled fuel; followed by a hand-held igniter; followed by 1 gallon of 75/25 gelled fuel; followed by 2 gallons of fresh crude. The remainder of the test procedures were the same as described above for the unemulsified oil burns.

The emulsion burn efficiency was calculated on an oil-only basis by comparing the weight of the residue with the weight of oil in the emulsion added initially as given by equation 3 below. This calculation assumes that the residue is essentially water-free. The burn rate was calculated by dividing the volume of oil burned out of the emulsion by the area of the ring on fire as a function of time, as given by equation 4 below.

$$\text{Burn Efficiency (\%)} = \frac{(\text{Initial Mass of Oil in Emulsion - Residue Mass}) \times 100}{\text{Initial Oil Mass}} \quad (3)$$

$$\text{Burn Rate (mm/min)} = \frac{(\text{Initial Mass of Oil in Emulsion - Residue Mass})}{(\text{Density of oil})(\text{Burn Area})(\text{Burn Time})} \quad (4)$$

The same definitions of burn time were used in equation 4 as were used in equation 2.

3.0 Results

The full data sets for each of the burns, along with the weather data for the test period (August 27 through September 3, 1997), may be found in the project report (SL Ross, 1998). A total of 58 experimental burns were conducted, 31 with ANS crude and 27 with Milne Pt. crude. The water temperature in the tank ranged from 3 to 9 °C (37 to 48 °F) over the course of the tests; air temperatures ranged from 0 to 4 ° C (32 to 40 °F). The wind speed at the anemometer on the command trailer ranged from 0.25 to 13 m/s (0.5 to 30 mph). Most tests were conducted in winds of 2 to 8 m/s (5 to 20 mph).

3.1 Alaska North Slope Crude Burns

Figure 8 shows the results of the 1.7 m diameter burns conducted with 5, 10 and 20 mm thick slicks of fresh ANS crude in four wave conditions (steepness, or H/λ, of 0, 0.03, 0.05 or 0.06). All these test slicks were successfully ignited with a 120 mL (4 fl oz) gelled gas igniter. This data set is the only one that involved tests with a wave steepness of 0.06. Two test burns were attempted at this setting. This wave setting was found to set up a standing circular wave inside the burn ring that highly disturbed the oil slick.

Figure 8a shows the calculated burn rate as a function of wave steepness. The deleterious effect of the standing wave at a steepness of 0.06 is clear. It appears that increasing wave steepness slightly decreases burn rate. This is the opposite of the effect noted in the lab-scale burns (40 cm diameter) where the burn rate increased with increasing wave steepness (see Buist *et al.*,1997). The reason for this different trend is unclear, but is probably related to the relative size of the burn in relation to the wave length. In the small-scale burns the fire diameter was only 12% of the low energy wave length; and 20 % of the high energy wave length. In the outdoor tank the burn diameter was 36% of the wave length.

It may also be that the two fire sizes are controlled by different processes: the heat transfer that drives the oil vaporization in the small-scale fires may have a significant convective component that is enhanced by wave action whereas the heat transfer in the larger fires may be dominated by radiation that is less affected, or even reduced, by wave mixing of the slick. It was also unusual that the 20 mm thick slick burned consistently slower than the 10 and 5 mm thick slicks. A repeat burn was conducted with the 20 mm thick slick to confirm this. Normally, the trend is for a slight increase in burn rate with increasing slick thickness, as was seen with the ANS crude in the small-scale tests and with the Milne Pt. crude (see below). The burn rates for the 5 and 10 mm thick slicks in calm conditions are in the range of other data for crude oil *in situ* burn rates (e.g. Buist *et al.*, 1994).

Figure 8b shows the effect of wave steepness on the burn time. For the thinner slicks, there appears to have been little effect; however, for the 20 mm thick slicks, an increase in wave steepness increases burn time. This is also somewhat inconsistent with the small-scale burn results (see Buist *et al.*,1997); for these there was also little effect of wave steepness for the thinner slicks but the burn time decreased with increasing slick thickness. The reason for the discrepancy is unknown.

Figure 8c shows the effect of wave steepness on burn efficiency. Discounting the 0.06 wave steepness data points, there does not appear to be a discernable trend, as was the case in the small-scale tests. The effect of the standing wave on the burn efficiency at a wave steepness of 0.06 is quite apparent; the increased slick disturbance caused a dramatic decrease in removal efficiency.

Although there is considerable scatter in the data shown in Figure 8d there may be an increase in residue remaining with increasing wave steepness, as was the case for the small-scale tests. The behavior of the 20 mm thick slick was unusual; one test resulted in almost 21 kg of residue and an identical repeat test resulted in 11 kg of residue. Both of these are much higher than the expected two to three kg.

Figure 9 gives the results of the mid-scale test burns with 20.4% evaporated, unemulsified ANS crude slicks. All of these test slicks were successfully lit with a single 120 mL (4 fl oz) gelled gas igniter. Figure 9a shows the calculated burn rate as a function of wave steepness. The burn rates for the evaporated oil were slightly lower than for the equivalent slick of fresh oil, as is expected (Bech *et al*., 1993). As with the fresh oil, the trend appears to be for burn rate to decrease with increasing wave steepness. This is also not in agreement with the small-scale burn test results which showed an increase, or no change, in burn rate with increasing wave steepness (Buist *et al*.,1997). Figure 9b shows the burn time plotted against wave steepness. The burn time for the thinner slicks (5 and 10 mm) did not seem to be affected by wave steepness. The burn time for the 20 mm thick slick appears to increase as the waves get steeper; the opposite trend was observed for the small-scale burns.

Figure 9c gives the burn efficiency as a function of wave steepness. Although the scatter is considerable, the trend appears to be of slightly declining oil removal efficiency with increasing waves, as was the case with the small-scale burns. This trend is further reflected in the burn residue data shown in Figure 9d.

3.2 Emulsified ANS Crude Burns

Figure 10 shows the results for the test burns with water-in-oil emulsions of 20.4% evaporated ANS crude. All of these tests involved 20 mm thick slicks.

It was during this series that it was discovered that the water being used to emulsify the oil was only brackish and the emulsions created were thus not fully stable. All of the 25% water emulsions were created with brackish water (10 ppt) as opposed to normal sea water (35 ppt). For the first 50% water emulsion burn the emulsion was not stable and was easily ignited (with only four gelled crude igniters). A repeat test was conducted with an emulsion made with 35 ppt salt water; this ultimately required 8 L (2 gallons) of fresh crude for ignition and burned sporadically with several instances of the fire dying down then flaring back up. This was more typical behavior for ANS emulsion fires (Buist *et al*., 1996 and 1997; SL Ross, 1995). All subsequent tests (all the 50% and 60% emulsion burns shown on Figure 10 and all the Milne Pt. crude emulsion tests) were conducted with emulsions created with 35 ppt salt water. Samples of these emulsions taken just after their creation did not visually break over a three-day period.

All the ANS emulsion burns after the 50% water test in calm conditions required the application of EXO 0894 emulsion breaker, a 45 minute waiting period and 8 L (2 gallons) of fresh crude for successful ignition. The emulsion was manually mixed in then allowed to work for approximately 45 minutes for all tests. Even the low wave setting proved too vigorous for the treated slicks, resulting in considerable dispersion losses beneath the ring. An amplitude setting of 0.8 with a frequency setting of 6.0 (creating a very long, low wave) was used for the settling period for all subsequent tests involving waves.

Figure 10a shows the effect of wave steepness on the oil burning rate for the three emulsion water contents. The data point for the 50% water content test in high waves should be ignored; this resulted from the high dispersion rate of the treated slick causing a considerable amount of the slick to escape beneath the skirt of the burn ring. Although there is a lot of scatter in the data, there appears to be a trend of slightly increasing burn rate with increasing wave steepness, as was the case for the treated emulsion slicks in the small-scale tests (Buist *et al.*, 1997). This similar trend at different scales indicates that something different is controlling the rate of oil burning in emulsions as compared to unemulsified oil slicks. This is probably the rate that oil separates from the emulsion to form a water-free slick on top of the emulsion.

Figure 10b shows the burn time as a function of wave steepness. Again discounting the 50% water data point in the high waves, there is a trend of decreasing burn time with increasing wave steepness, as was the case for the small-scale burns. Figure 10c shows the effect of wave steepness on burn efficiency. Excluding the 50% water, high waves data point, there is little correlation. The oil removal efficiency for the 50% water slicks decreased and the removal efficiency for the 60% water slicks increased with increasing waves. Figure 10d shows similarly scattered data for the amount of residue remaining after each burn.

3.3 Milne Pt. Crude Oil Burns

Figure 11 shows the results of the 1.7 m diameter burns conducted with 5, 10 and 20 mm thick slicks of fresh Milne Pt. crude in three wave conditions (steepness, or H/λ, of 0, 0.03 or 0.05). All these test slicks were successfully ignited with a 120 mL (4 fl oz) gelled gas igniter. Figure 11a shows the effect of wave steepness on burn rate. The data points for the 20 mm slicks in waves are artificially high due to significant amounts of oil leaking out from the boom and burning outside the burn ring. The boom was replaced after these two tests. The data for the thinner slicks is scattered, but appears to indicate a trend of decreasing burn rate with increasing wave steepness, as was noted for the ANS crude slicks at this scale. No equivalent small-scale burn tests were conducted with this oil. The burn rates calculated for the Milne Pt. crude were about the same as those calculated for the fresh ANS crude, with the exception of the anomalous results obtained for the 20 mm thick ANS slicks (see above).

Figure 11b shows the burn times plotted against wave steepness. For the thinner slicks there appears to be no effect of wave steepness on burn time, as was the case for the equivalent fresh ANS crude burn tests. The lower burn times noted for the 20 mm slick in the waves were a result of the oil losses from the boom for these tests. Figure 11c shows the effect of wave steepness on burn efficiency. Discounting the 20 mm burns in waves, for the reason noted above, there is little effect of wave steepness on burn efficiency for the 5 mm slick, but perhaps a reduction in efficiency at the highest wave setting for the 10 mm slick. Figure 11d gives the burn residue data; again discounting the 20 mm slick tests, there was no discernable trend in residue left versus wave steepness, as was the case for the fresh ANS burn tests.

Figure 12 summarizes the results for the mid-scale burn tests with the 27.6% evaporated, unemulsified Milne Pt. crude. Figure 12a shows the effect waves on the calculated burn rate. There is a clear trend of lower burn rate with higher wave steepness, as was noted for the equivalent evaporated ANS test burns. The 20 mm slicks had lower burn rates than the thinner slicks. The reason for this is not clear, and may be due only to measurement errors. The burn rates for the Milne Pt. crude slicks in calm conditions were significantly higher than for the similar ANS tests. This may be a reflection of higher volatility of the evaporated Milne Pt. crude. The burn time results, shown in Figure 12b, show a weak positive relationship between the length of the burn and increasing wave steepness. There appears to be a strong positive relationship for the 20 mm thick slick. This is consistent with the results for the equivalent ANS tests.

Figure 12c shows the burn efficiency declining somewhat with increasing wave steepness for all three slick thicknesses. This is consistent with the results for the comparable ANS test burns.

Figure 12d shows the effect of wave steepness on burn residue. An increase in residue amount with increasing wave steepness is apparent.

3.4 Emulsified Milne Pt. Crude Burns

Figure 13 gives the results of the test burns with emulsions of Milne Pt. crude. All of these tests involved 20 mm thick slicks. All the emulsions were created with 35 ppt salt water. Samples of these emulsions taken just after they were created did not break over a two-day observation period. As was the case with the small-scale tests (SL Ross, 1998) most of the emulsions were easily ignited with only a single gelled gas igniter; only the 60% water emulsions in waves required the more powerful ignition source of four gelled crude igniters. None of the emulsions required the application of the emulsion breaker to promote ignition and burning. This was also observed in the small scale tests, but was very different than the situation for the ANS emulsion burn tests, most of which did require emulsion breaker for successful ignition.

Figure 13a shows that there was little effect of wave steepness on burn rate of the emulsions. This was the same as what was observed with the small-scale tests (SL Ross, 1998). In the case of the mid-scale ANS emulsion burns there appeared to be an increase in burn rate with increasing wave steepness. The different behaviors for the two oils may relate to the different stability indices of the emulsions; the ANS emulsions required emulsion breaker to separate; the Milne Pt. emulsions would separate and burn with only the application of heat. This was apparent in observing the progress of the flame spread over the Milne Pt. emulsions; a band of black oil could be seen appearing ahead of the flame front as it spread across the emulsion. Comparing the burn rate of the Milne Pt. emulsions in calm conditions, the typical reduction in oil removal rate with increasing water content is apparent, as it was with the comparable ANS emulsion burns. Figure 13b shows the burn times as a function of wave steepness. The burn time does not appear to depend on the wave steepness. In comparison, the burn time for the equivalent burns with ANS emulsions decreased with wave steepness. This may also be related to emulsion stability differences.

Figure 13c presents the effect of waves on the burn efficiency. There is considerable scatter; however, there appears to be little or no effect, as was the case for the comparable ANS emulsion burns. In the case of the small-scale burns with Milne Pt. emulsions in the lab (SL Ross, 1998), there appeared to be a slight reduction in burn efficiency with increasing wave steepness. The burn residue data in Figure 13d is too scattered to indicate any correlation of residue amount with wave steepness, as was the case for the ANS emulsions.

4.0 Conclusions and Recommendations

4.1 Conclusions

The mid-scale burn tests showed that larger oil and emulsion slicks of ANS and Milne Pt. crudes could be successfully burned in waves. Emulsified slicks of ANS crude with water contents greater than 25% required treatment with emulsion breakers and a period of settling for successful ignition and efficient burning. The Milne Pt. emulsions ignited and burned easily without treatment.

A mid-scale test slick of 60% water emulsion of weathered ANS crude was successfully burned in the highest waves tested, with an oil removal efficiency of 79%, after treatment with emulsion breakers. A similar test slick of 60% water emulsion of weathered Milne Pt. crude was successfully burned in the highest waves tested, without the need for treatment with emulsion breakers, with an oil removal efficiency of 83%.

At this larger scale, increasing wave steepness (or wave energy) appeared to reduce both burn rates and burn efficiencies of the unemulsified oil slicks. For emulsified slicks, increasing wave steepness did not appear to appreciably affect the oil burning rates, but did reduce the oil removal efficiencies.

Comparing the results of the lab burns (Buist *et al.*, 1997; SL Ross, 1998) with the mid-scale tests, it appears that the lab tests were a good predictor of the likely success of ignition and the oil removal efficiency for the mid-scale tests; however, they did not adequately predict trends in oil burn rate as a function of wave steepness at the larger scale.

4.2 Recommendations

These mid-scale tests have indicated that the technique of adding emulsion breakers to extend the window of opportunity for *in situ* burning of Alaskan oils continues to show promise; however, in themselves, they are not sufficient to conclude that the operational use of emulsion breakers offshore is feasible. In order to implement emulsion breaker addition as a technique to extend the window of opportunity for ISB operations offshore several areas still need to be researched. These include:

i) exploring the regulatory regimes covering the application of emulsion breakers to oil slicks, and, if required, obtaining approval for specific chemicals being considered for ISB;
ii) investigating and developing systems for the application, and perhaps mixing, of emulsion breakers at dose rates on the order of 1:500 onto contained slicks at sea;
iii) conducting large-scale trials in realistic wave conditions (i.e., on the order of 0.6 to1 m high) to fully prove the operational feasibility of burning water-in-oil emulsions *in situ*. Although ideally these trials should be conducted at sea, tests in a large pit or other water body could serve as a substitute. These tests are necessary to confirm that, in an offshore environment: the emulsion breaker can be applied and work effectively over a large area of slick; that the flames will spread from an area ignited with a Heli-torch to cover the entire slick; and, that an efficient burn will result that removes a significant amount of the oil.

5.0 Acknowledgements

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6.0 Disclaimer

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Table 1: Wave Characteristics as a Function of Controller Settings

Frequency Setting	Amplitude Setting	Period (s)	Length (m)	Height (cm)	Steepness Ratio
6	1		>7.3	13	<0.017
7	1		>7.3		
7.5	1		7.3	18	0.024
7.8	1		6.7	18	0.027
8.001	0.8	2	4.8	15	0.031
8	1		4.8	19	0.039
8.052	1.4	1.96	4.7	23	0.048
8.10 [3]	1.4	1.9	4.2	28	0.065
8.1	1.7		4.2	25	0.06
8.2	1.4		4.2	30	0.072
8.25	1.4		4.2	30	
8.3	1.2		4.2	23	0.054
8.5	1		3.3	15	0.045

[1] this was the "low" energy wave setting used for the burn tests

[2] this was the "high" energy wave setting used for the majority of the burn tests

[3] this was the "high" energy wave setting used for the first few burn tests

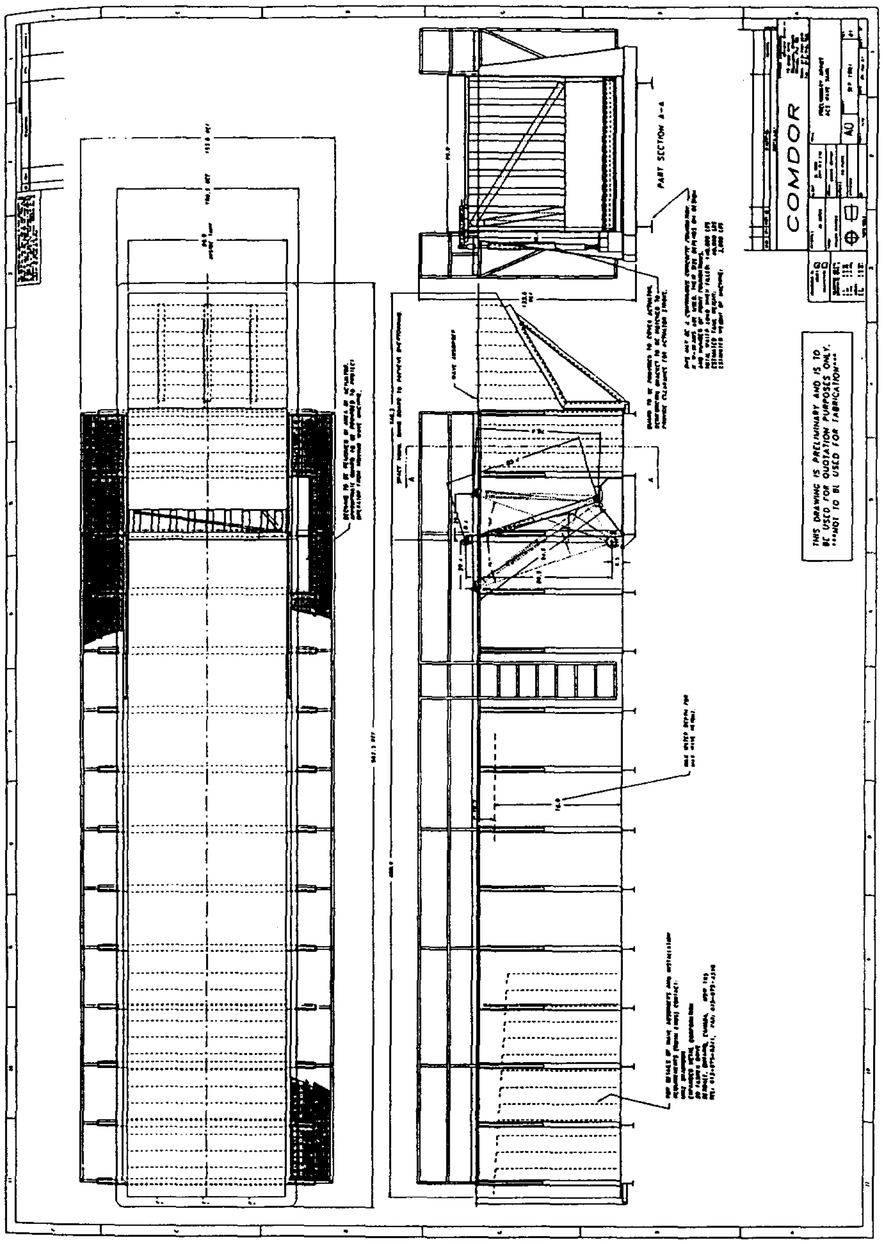

Figure 1 - Preliminary Tank Layout

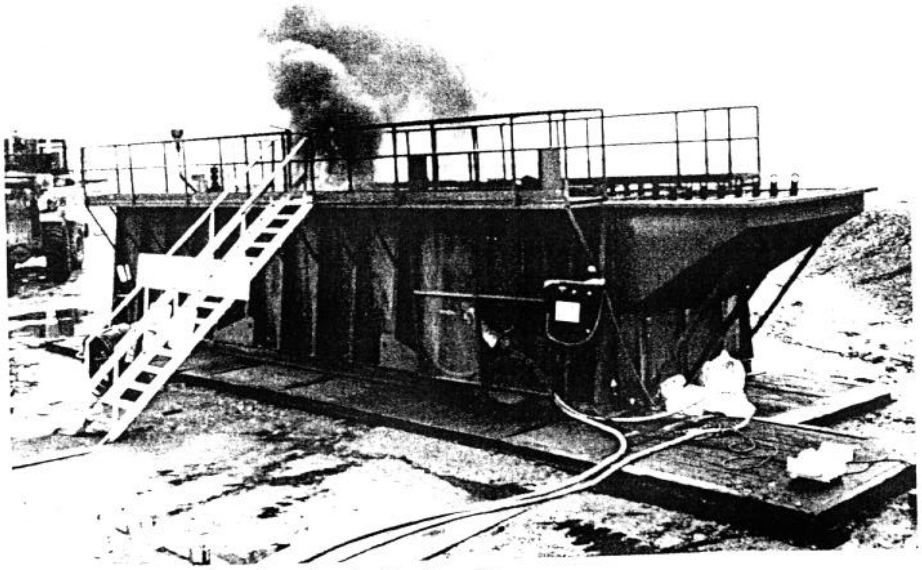

Figure 2: Wave tank on location in Prudhoe Bay

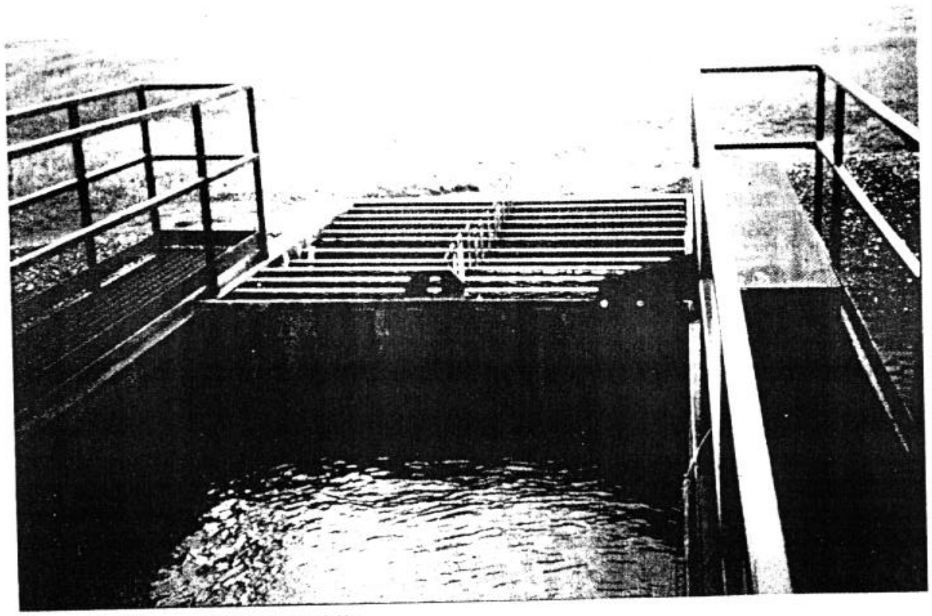

Figure 3: Wave generator paddle

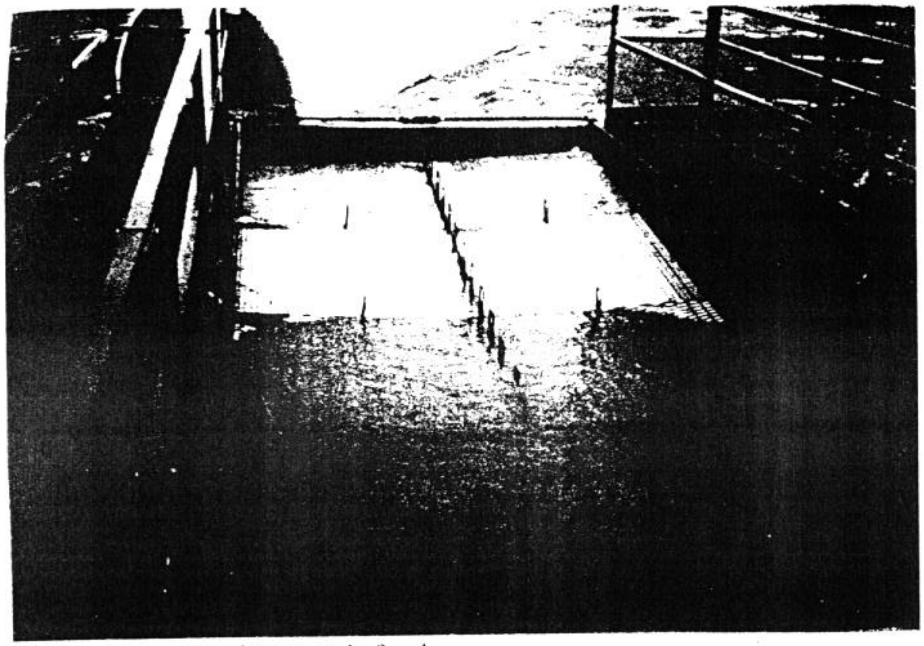

Figure 4: Wave absorbers at end of tank

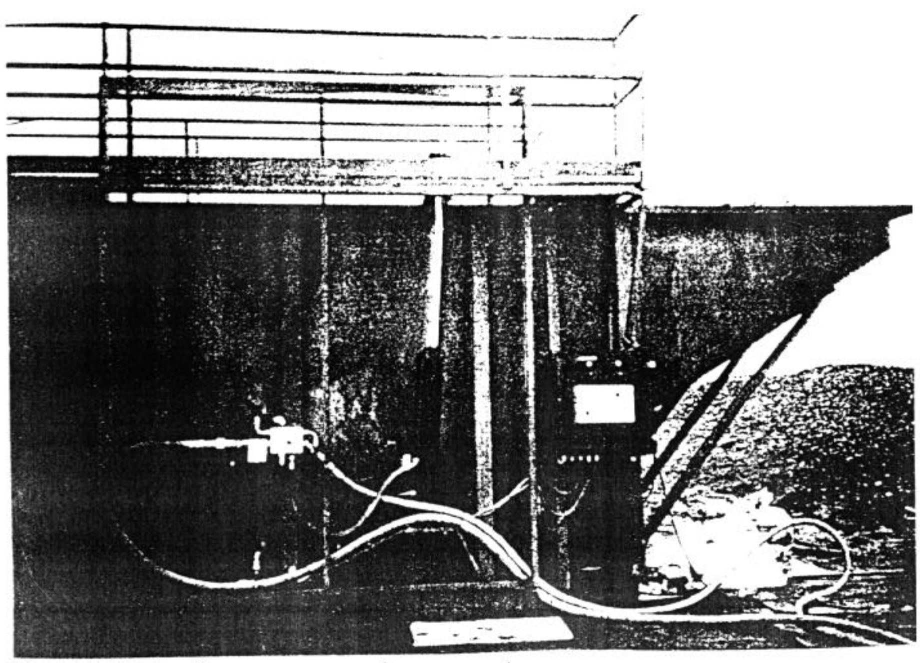

Figure 5: Hydraulic power system for wave maker

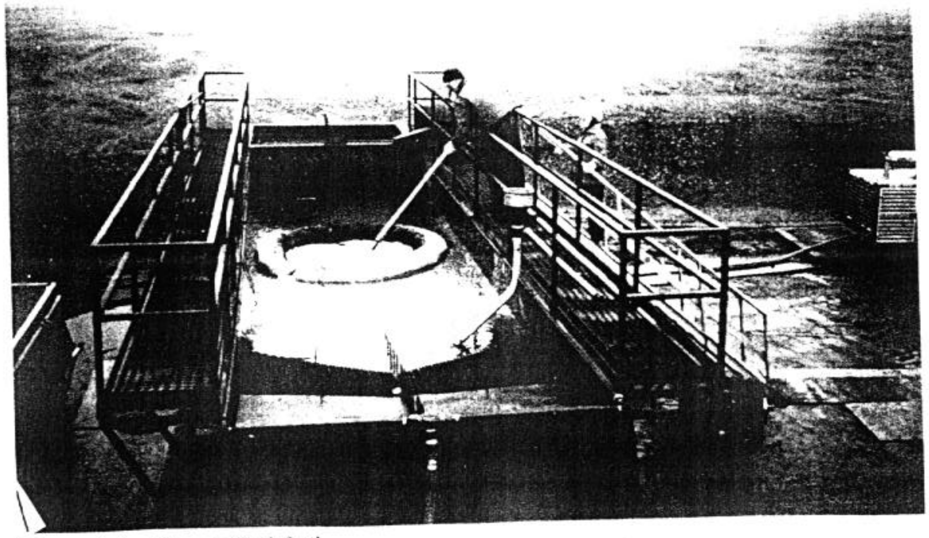

Figure 6: Igniting gelled fuel

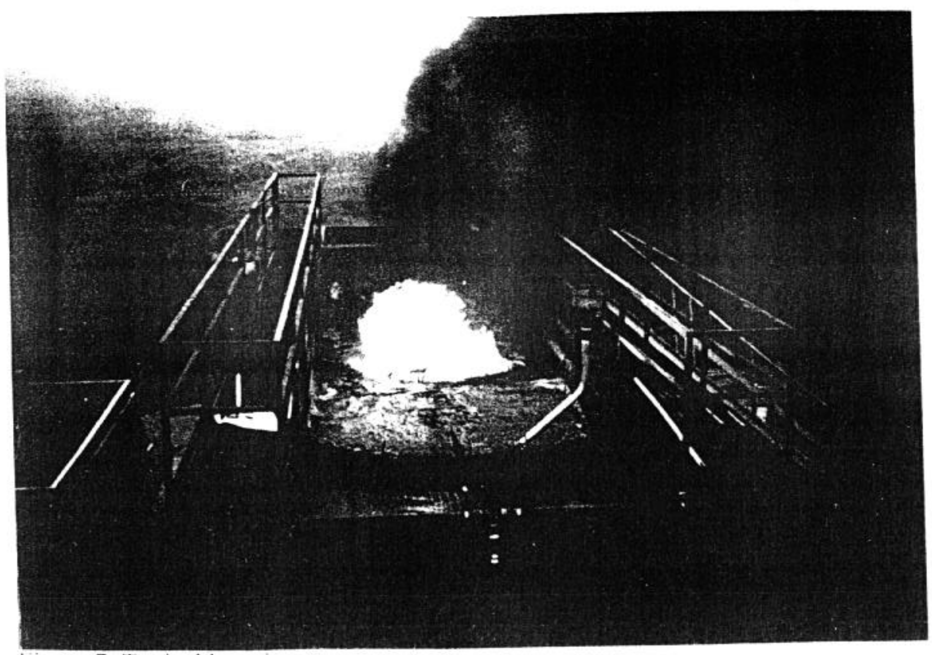

Figure 7: Typical burn in waves

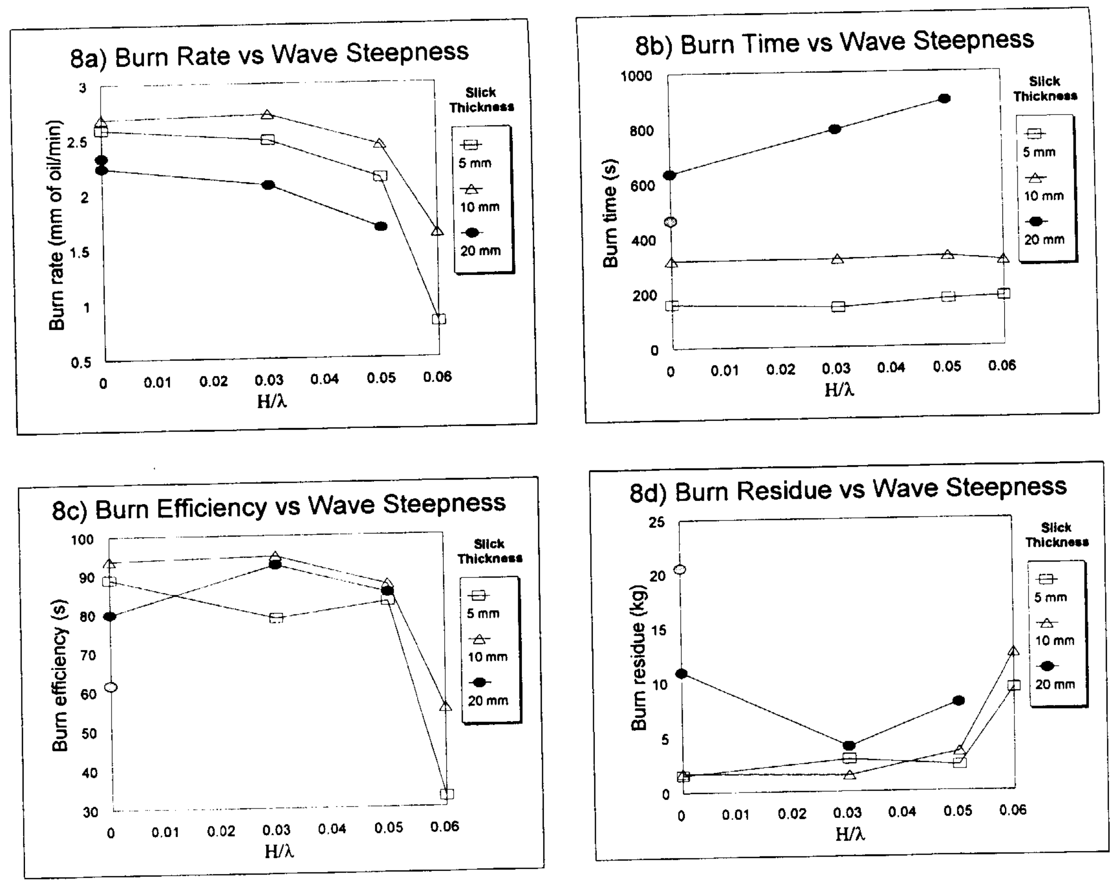

Figure 8: Mid-scale Burns with Fresh ANS in Waves

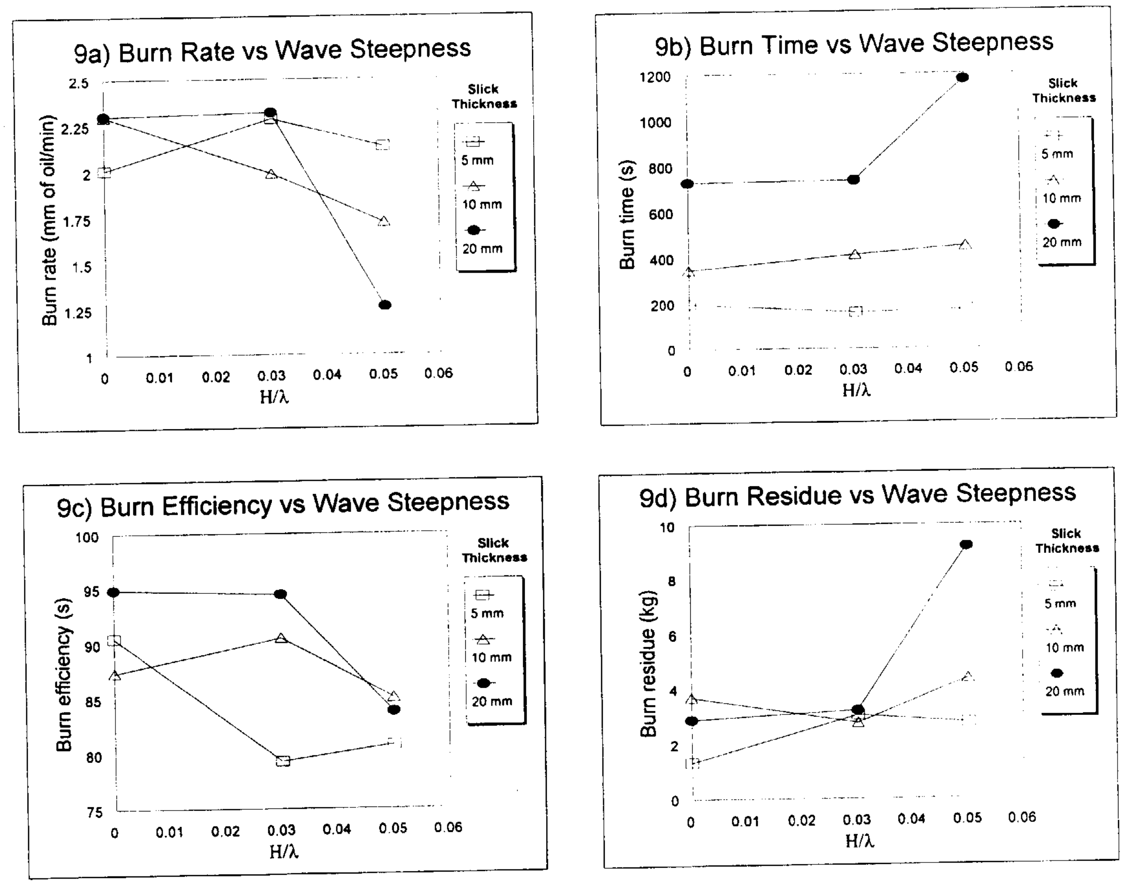

Figure 9: Mid-scale Burns with 20.4% Evaporated ANS in Waves

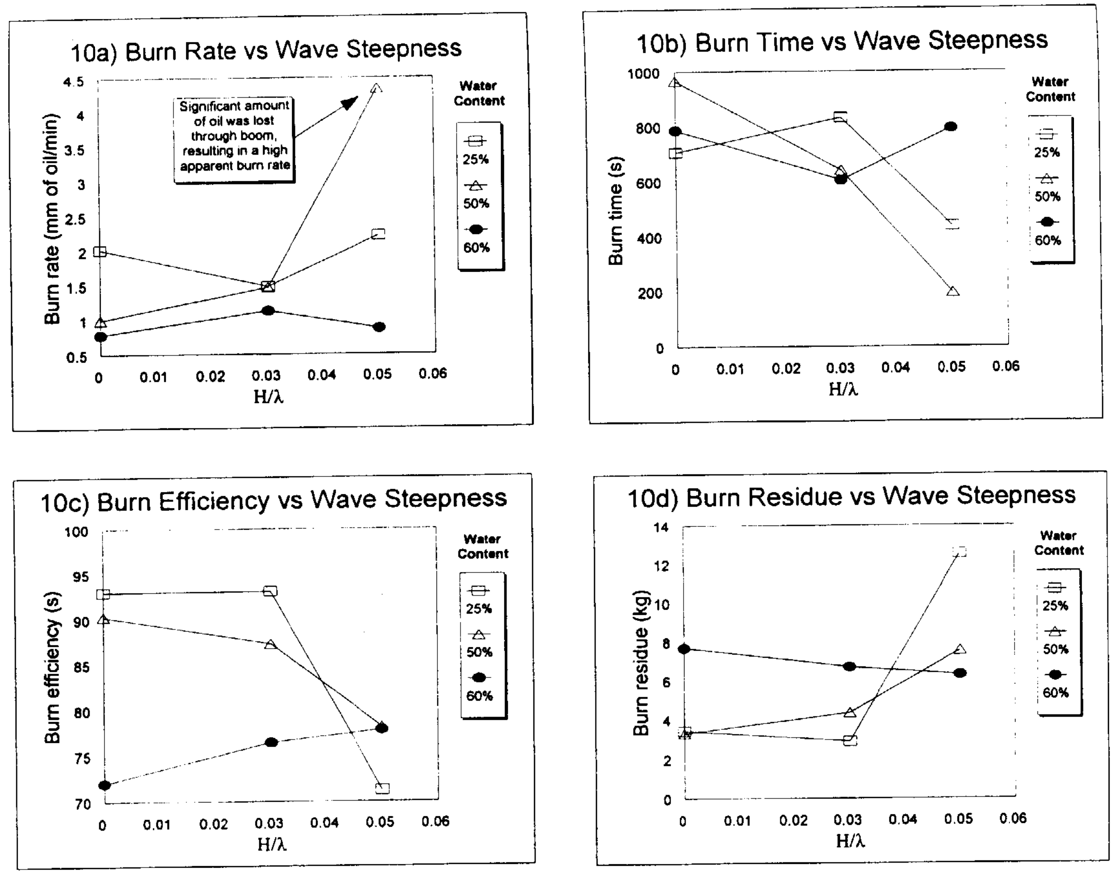

Figure 10: Mid-scale Burns with Emulsified ANS in Waves (20 mm slicks)

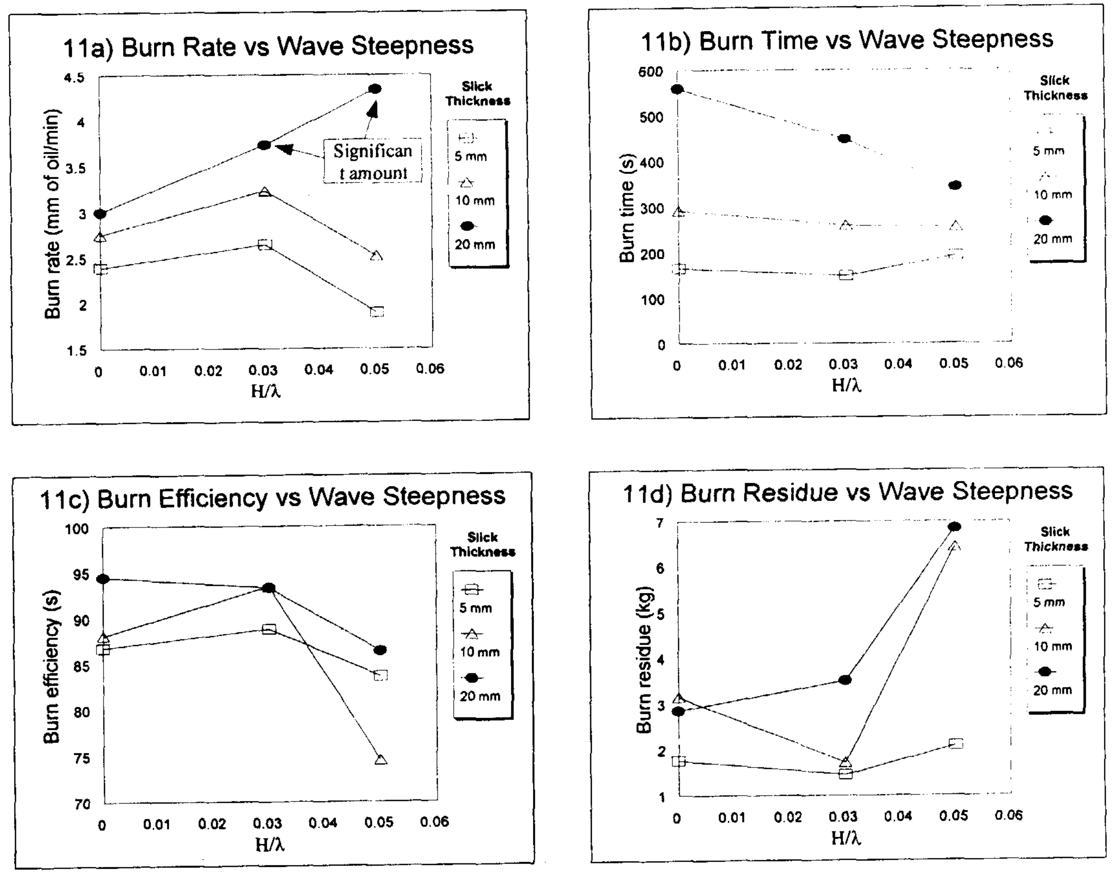

Figure 11: Mid-scale burns with Fresh Milne Pt. in Waves

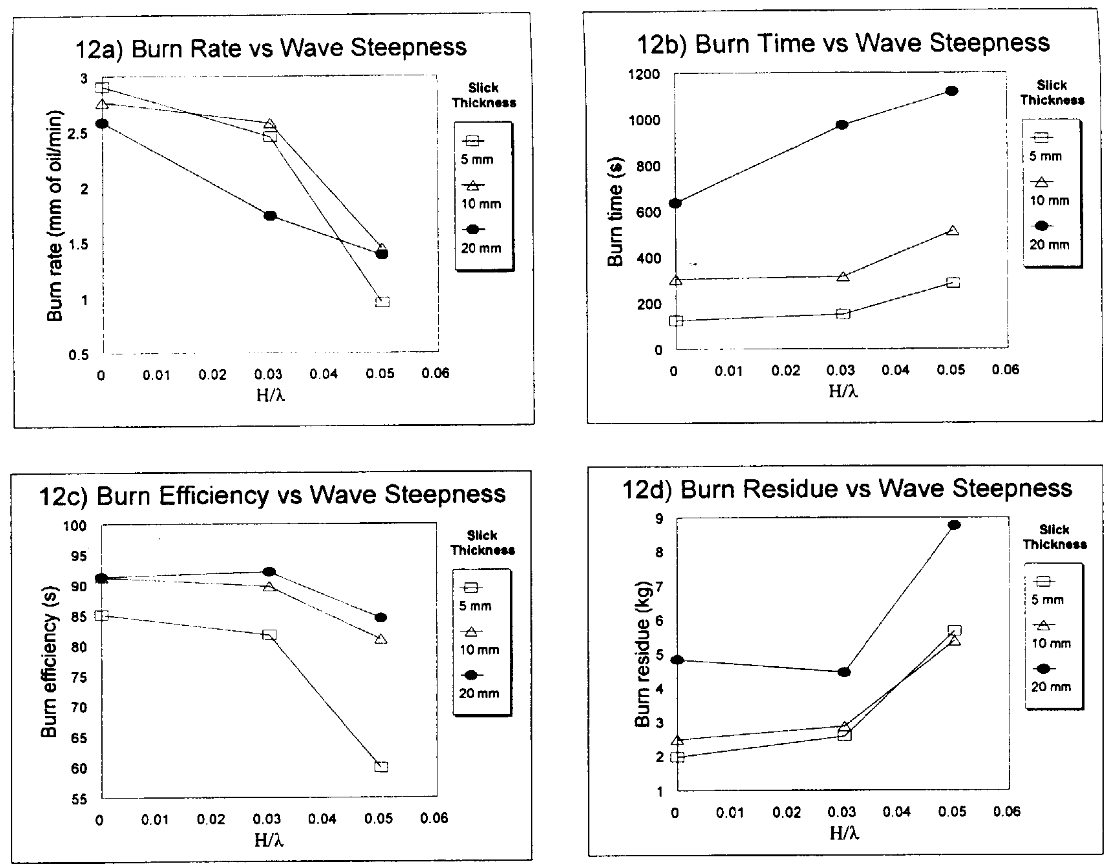

Figure 12: Mid-scale Burns with 27.6% Evaporated Milne Pt. in Waves

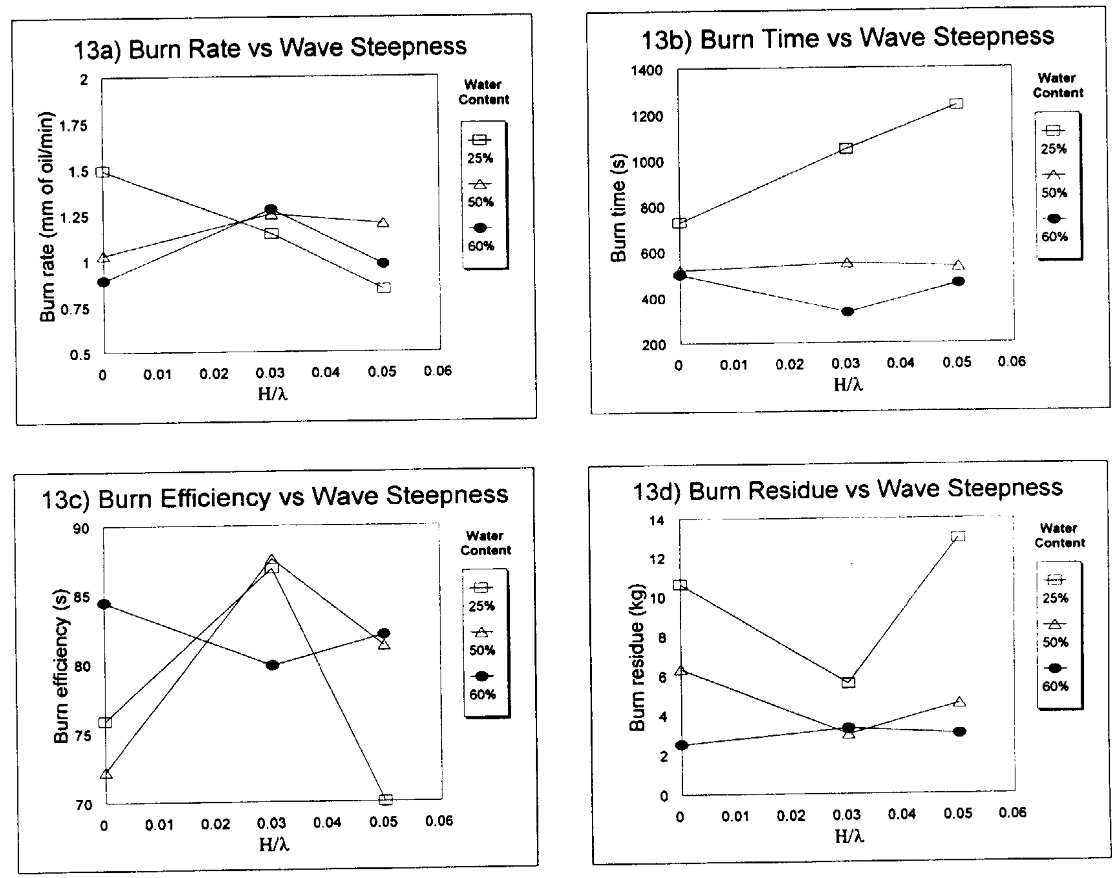

Figure 13: Mid-scale Burns with Emulsified Milne Pt. in Waves