

**LABORATORY TESTING TO DETERMINE
OPERATIONAL PARAMETERS FOR IN SITU BURNING
OF SIX U.S. OUTER CONTINENTAL SHELF CRUDE OILS**

**Prepared for the
United States Department of the Interior
Minerals Management Service
Herndon, VA**

**by
S.L. Ross Environmental Research Ltd.
Ottawa, ON**

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Executive Summary

The Minerals Management Service (MMS) initiated a laboratory test program to determine the following parameters with respect to the *in situ* burning of six U.S. Outer Continental Shelf (OCS) crude oils:

- limits to ignition using gelled gasoline igniters imposed by evaporation and emulsification;
- the ability of commercially-available emulsion breakers and alternative fuel igniters to extend the window-of-opportunity for ignition of stable emulsions;
- the effects of wave action on the combustion of emulsion slicks; and,
- the likelihood of the residues sinking after efficient burns of thick slicks of the crude oils.

Before oil spill response plans are developed or approved, it is important to understand the physical behavior of the spilled oil and how it changes over time. The *Catalog of Crude Oil and Oil Products Properties*, jointly funded MMS and Environment Canada contains the physical and chemical data of over 380 different types of about oils, including some information on dispersibility. This research study is intended to provide additional data which should be considered when developing oil spill response plans. For these six OSC crude oils, we now have the information required to make an informed decision regarding the *window of opportunity* for various response options. and can coordinate a multi-approach response involving burning, dispersing and skimming

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- Mr. Steve Lawry and Mr. Lyman Young from Chevron U.S.A. for providing the Santa Clara crude oil;
- Mr. Robert Radnotti of Exxon U.S.A. for providing the Santa Ynez crude oil;
- Mr. David Rose of Torch Operating Company for providing the Carpinteria crude oil;
- Mr. Kent Satterlee and Mr. Bela James of Shell Offshore Inc. for providing the Green Canyon Block 65 crude oil; and
- Mr. Robert Simmons of Exxon U.S.A. for providing the West Delta Block 30 crude oil;

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1. Introduction

In situ burning 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 water-in-oil emulsions can quickly lead to an oil becoming not ignitable, thus ending the possibility of a successful *in situ* burn.

Recently, research has focused on extending the window-of-opportunity for *in situ* burning by developing more powerful igniters, and investigating the use of chemical surfactants that break water-in-oil emulsions (S.L. Ross, 1995, Guénette et al., 1994). The studies concluded that the burning process for water-in-oil emulsions is much more complex than for water-free oil (Bech et al., 1993) and that success at breaking and burning depends on oil-specific factors (Strøm-Kristiansen et al., 1995).

In light of this dependency on oil properties, it is vital that specific oils be tested to determine the suitability of *in situ* burning as a response. Data for each oil must be collected on the effects of oil evaporation and emulsion formation on ignitability, burn rate and oil removal efficiency, and the potential for emulsion breakers to extend the window-of-opportunity. Burn tests should be conducted with each selected oil in a range of conditions and with a variety of commercial chemical surfactant products.

Another concern that must be addressed is the fate of the residue from a successful *in situ* burn, specifically whether it would be buoyant. Recent experiences that involved accidental burning on the sea of large volumes of heavy crude oils during actual spills (Moller, 1992, Turbini et al., 1993) and recent large-scale experiments involving thick slicks of moderately heavy oil (Buist et al., 1995) have shown that some burn residues may sink. Clearly, the propensity of the burn residue of an oil to sink should be determined prior to implementing an *in situ* burn.

1.1 Objective

The Minerals Management Service, in consultation with their Gulf of Mexico and Pacific Regional Offices selected six U.S. OCS crude oils and subjected them to a laboratory test program. The oils selected by the Gulf of Mexico region were:

- Amoco High Island crude oil,
- Green Canyon Block 65 crude oil,
- West Delta Block 30 crude oil

The oils selected by the Pacific Region were:

- Carpinteria crude oil,
- Santa Clara crude oil
- Santa Ynez crude oil.

The objective was to determine the following *in situ*-burning-related parameters:

- limits to ignition using gelled gasoline igniters imposed by evaporation and emulsification;
- the ability of commercially-available oil spill emulsion breakers and alternative fuel igniters to extend the window-of-opportunity for ignition of stable emulsions;
- the effects of wave action on the combustion of emulsion slicks; and,
- the likelihood of the residues sinking after efficient burns of thick slicks of the crude oils.

The laboratory test procedures are described in Section 2 and the results are presented in Sections 3 through 8. The raw data for the tests can be found in the Appendices.

2. Test Procedures

This section describes the test procedures that were used to evaluate the *in situ* burning related characteristics of the six oils.

2.1 Evaporation

Evaporation is one of the most significant processes that affects an oil when it is spilled. Evaporation removes the volatile, light hydrocarbons from the crude oil and leaves behind the heavier fractions. From the perspective of *in situ* burning, this results in the oil becoming progressively more difficult to ignite. Although high degrees of evaporation alone will not necessarily preclude the use of burning, it can when combined with other factors, such as high sea states, high wind or emulsion formation.

To assess the effect of evaporation on the ignition and burning characteristics of each oil, the oils were artificially evaporated. First, one 450-mL sample of each oil was weathered in a wind tunnel for one week, in order to quantify the rate and extent of evaporation that would occur if the oil was spilled at sea. The wind speed in the tunnel was approximately 3 m/s, measured 1 cm above the oil surface, and the air temperature averaged 24°C. The mass of oil remaining in the trays was measured regularly. The wind tunnel was calibrated during the oil evaporation so that the duration of exposure to evaporative forces in the wind tunnel could be correlated with exposure during a spill.

Based on a hypothetical spill scenario of a 2-mm thick slick, a water temperature of 24°C and a 2.5 m/s wind, and the wind tunnel mass loss data, the degrees of evaporation corresponding to 8 and 27 hours on the ocean in the same conditions were calculated for each oil. These were chosen to represent a range of achievable response times to a spill. While this calculation results in different degrees of evaporation for each oil, it represents the equivalent exposure to evaporative forces.

These values were used as the endpoints for the evaporation of the samples to be used in the emulsion formation-tendency and stability, emulsion breaking, and burning experiments. This was accomplished by bubbling compressed air through two or more heated 20-L batches of each oil in buckets until the desired mass fractions has been evaporated.

2.2 Emulsion Formation-Tendency and Stability

A key problem that remains with the use of *in situ* burning is the potential for the oil to form a stable water-in-oil (W/O) emulsion. The presence of as little as 25% emulsified water in a slick will usually prevent ignition and burning of the oil. Even if the W/O emulsion is less than fully stable and thus burnable, the presence of water in the oil significantly increases the heat required to ignite it.

The tendency of the oils to form an emulsion and the stability of the resulting emulsion were determined using the standard rotating flask technique (Zagorski and Mackay, 1982). The test was conducted on both the fresh and weathered samples, at a temperature of 20°C.

The procedure was as follows:

- 30 mL of oil was added to a 500-mL fleaker¹ filled with 300 mL of 35-ppt salt water and sealed;
- the initial height of the oil was recorded;
- the fleaker was rotated at 60 rpm in a chamber maintained at 20°C;
- after one hour, the height of the emulsion and oil layers were measured following each of 5, 10, 20 and 30 minutes of settling; and,
- the process of rotation and settling was repeated for a total of four 1.5 hour cycles.

The heights of the emulsions formed were used to calculate two indicators: the emulsion formation-tendency index, and the emulsion stability index. Both indicators can have values

¹A fleaker is a cylindrical flask with a flared neck and pouring spout

between 0 and 1. Table 2-1 shows how to interpret the meaning of the indicators. Both the formation-tendency and stability indices increase with increasing degree of evaporation.

Table 2-1: Physical Meaning of Indicators

Indicator Value	Formation-Tendency Index	Emulsion Stability Index
0 to 0.25	Unlikely to form emulsion	Emulsion very unstable
0.25 to 0.75	Moderate tendency to form emulsion	Emulsion moderately stable
0.75 to 1	High tendency to form emulsion	Emulsion very stable

2.3 Emulsion Breaker Effectiveness

Chemical surfactants are available that lower the oil-water interfacial tension and promote the coalescence of water droplets in a W/O emulsion. This ideally causes it to separate. They are used extensively in the crude oil production and refining processes. Their effectiveness is oil-specific and dependent on the properties of the oil.

The effectiveness of three emulsion breaking chemicals (also known as demulsifiers) were tested on the weathered crude oil samples. They were:

- Alcopol 0 70% PG (Alcopol)
- Breaxit OEB-9 (Breaxit) and
- EXO-0894 (EXO),

Two dosage ratios of demulsifier to emulsion were used, 1 to 500 and 1 to 5000. The procedure used (Hokstad et al., 1993) was as follows:

- 1.5 L of 60% water emulsion was prepared by recirculating 900 mL of salt water (35 ppt) and 600 mL of oil through a gear pump;
- 150-mL samples of the emulsion were placed in each of seven 500-mL fleakers containing 200 mL of 35-ppt salt water;
- the initial heights of the emulsions were recorded (H_{REF});

- the appropriate volumes of emulsion breaker were added to six of the fleakers and allowed to soak into the emulsion for 5 minutes (see Table 2-2);
- the fleakers were rotated at 30 rpm for 5 minutes; and,
- the heights of the emulsions were recorded after 2 minutes (H_{IM}) of settling and after 24 hours (H_{24}).

Table 2-2: Brands and Volumes of Emulsion Breaker

Fleaker	Emulsion Breaker	Volume (ml)	Ratio of Demulsifier:Emulsion
1	Alcopol	0.3	1:500
2	Alcopol	0.03	1:5000
3	Breaxit	0.3	1:500
4	Breaxit	0.03	1:5000
5	EXO	0.3	1:500
6	EXO	0.03	1:5000
7	None (control)	0	N/A

A control fleaker, to which no emulsion breaker was added, to test if the emulsion would break naturally. The gear pump makes emulsions that are more stable than those that form naturally from wave action. The results of the emulsion breaker effectiveness test can therefore be considered as conservative. Two of the oils tested were too viscous for the gear pump and the emulsions were made using an electric drill with a paint mixing attachment. The measured heights of emulsion in the fleakers were converted to water:oil ratios according to equations (1), (2) and (3).

$$W:O_{REF} = 1.5 \quad (1)$$

$$W:O_{IM} = \frac{H_{IM}}{H_{REF} \times 40\%} - 1 \quad (2)$$

$$W:O_{24hr} = \frac{H_{24hr}}{H_{REF} \times 40\%} - 1 \quad (3)$$

Where: $W:O_{REF}$ is the initial water to oil ratio of 1.5 parts water to 1 part oil

$W:O_{IM}$ is the water to oil ratio after 2 minutes of settling

$W:O_{24hr}$ is the water to oil ratio after 24 hours of settling

The effectiveness of the demulsifier was characterized by the achieved percent dehydration, which is the reduction in amount of water in the emulsion expressed as a percentage of the initial water. For example, a dehydration of 75% means the final emulsion has only 25% of the water it had to begin with. For a starting emulsified water content of 60%, this would produce a final emulsion with a water content of 27%.

The percent dehydration was calculated immediately (i.e., after two minutes) and after the twenty-four hour settling period, according to equations (4) and (5).

$$\% \text{ Dehydration}_{IM} = \frac{W:O_{REF} - W:O_{IM}}{W:O_{REF}} \times 100\% \quad (4)$$

$$\% \text{ Dehydration}_{24hr} = \frac{W:O_{REF} - W:O_{24hr}}{W:O_{REF}} \times 100\% \quad (5)$$

2.4 Baseline Burns

The limits to ignition imposed by evaporation and emulsion formation were determined for each oil by conducting a series of baseline burns. These tests also measured the burning characteristics of water-free and emulsified slicks of the fresh and weathered crude oils.

Beginning with the fresh oil, the water content of the emulsion to be tested was increased stepwise (from 0 to 25, 33, 50 and finally 60% water). This process was then repeated with the weathered oil samples.

The burns were conducted in a wave tank measuring 11 x 1.2 x 1.2 m (L x W x H) that was filled with water to a depth of 85 cm (see Figure 2-1). The air and water temperatures were maintained as close to 20°C as possible. The oil or emulsion was contained in a 40-cm diameter, steel ring, supported by a steel frame that rested on the bottom of the tank. For each test, 2.5 L of emulsion was used, which resulted in a 2-cm thick slick. The smoke from the burns was removed with a 200-m³/min fan through a 60-cm diameter flexible aluminum duct that was connected to a fume hood suspended 1.5 m above the steel ring.

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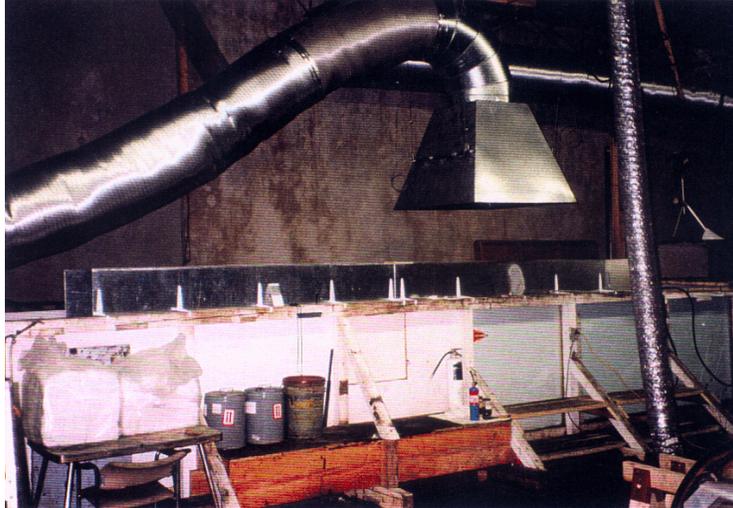


Figure 2-1: SL Ross Indoor Wind/Wave Tank

Emulsions were prepared just prior to each test by recirculating the appropriate volumes of crude oil and water through a small gear pump. The gear pump imparted considerable mixing energy and produced very stable emulsions; even emulsions created using weathered oils with low to moderate stability indices (as measured in the rotating flask apparatus) were very stable. Therefore, the limits to ignition reported can be considered conservative estimates. The system of choice for igniting crude oil slicks is the Heli-torch, which uses gelled gasoline for fuel. To simulate this source of ignition, 40 to 50 g of gelled gasoline were used to start the baseline burns.

The parameters measured for the baseline burns included:

- initial mass and volume of the oil or emulsion;
- mass of the burn residue;
- air and water temperatures;
- flame and oil or emulsion slick temperatures;
- preheat time (time from ignition of gelled gasoline to initial spreading of flame);
- ignition time (time from ignition of gelled gasoline to complete ignition of slick surface);
- time to intense burn (time to the beginning of the vigorous burn phase); and
- time to extinction of slick.

The efficiency and rate of each burn were calculated using equations (6) and (7), respectively. Burn efficiency was the ratio of the mass of oil burned to the initial oil mass. Burn rate was defined as the rate of decrease in the equivalent oil thickness of the slick over the period of the burn. For emulsion burns, the residue was assumed to be water free for calculating burn efficiency and burn rate.

$$\text{Burn Efficiency (\%)} = \frac{M_{oil, initial} - M_{residue}}{M_{oil, initial}} \times 100\% \quad (6)$$

$$\text{Burn Rate} = \frac{M_{oil, initial} - M_{residue}}{(\rho_{oil})(A_{ring})(T_{extinction} - T_{ignition})} \quad (7)$$

Where: $M_{oil, initial}$ is the initial mass of oil (g)

$M_{residue}$ is the mass of the residue (g)

ρ_{oil} is the density of the oil (g/mm^3)

A_{ring} is the surface area of the ring (mm^2)

$T_{extinction}$ is the time from application of the igniter to complete extinction of flames (min)

$T_{ignition}$ is the time from application of the igniter to complete ignition of the ring (min)

2.5 Emulsion Breaker Burns

Emulsion breaker burn tests were conducted on emulsions that were determined to be not ignitable due to their water content and/or evaporation in the baseline burn tests. The objective was to determine if the addition of emulsion breaker would allow the ignition of the slicks, and what affect it would have on the burning characteristics of the oils. The most effective chemical, as determined from the emulsion breaker effectiveness test (see Section 2.3) was used.

Emulsion breaker was added to the not ignitable slick at a dosage ratio of 1:500 (i.e., 5 mL of emulsion breaker). The emulsion breaker was mixed into the slick with a glass stirring rod for two minutes. After mixing, the emulsion was allowed to sit for forty minutes. After the settling period, gelled gasoline was used to try to ignite the slick. In most instances, if the gelled gasoline could not ignite the slick, another attempt was made using a 2-mm thick layer of fresh oil as a primer. The 2-mm layer of fresh oil represents the maximum strength of igniter that could reasonably be applied to large area of a real spill. If an oil could not be ignited with the fresh oil layer it was deemed not ignitable.

The same parameters were measured for the emulsion breaker burns as for the baseline burns.

2.6 Burns in Waves

Burn tests in waves were conducted to determine how waves affected the ignition and burn characteristics of each of the oils. A 40-cm diameter, floating containment ring was used for these tests. The waves were produced by paddle-board wave generator, located at one end of the tank. Two wave settings were used for the tests: low and high (see Table 2-2).

If the oil was amenable to the use of emulsion breakers with burning (see Section 2.5), further emulsion breaker burns were conducted in waves. These were performed with no pre-mixing of the breaker into the slick; the mixing was supplied by the wave action alone.

Table 2-2: Wave Properties

Property	Low Setting	High Setting
Wave Length (m)	3.3	2.0
Wave Period (s)	2.0	1.3
Wave Height (cm)	9 to 11	14 to 15
Wave Steepness	0.03	0.07
Energy (J/m ²)	123	184

The same parameters were measured for the burns in waves as for the baseline burns.

2.7 Residue Burns

Burns were conducted with 5 and 10 cm thick slicks of the fresh crude oils, and the residues collected.

For those residues that were fluid at 20°C, their densities were measured with an Anton Paar densitometer, model DMA 35. For those residue samples that were not fluid at 20°C, their densities were measured by immersing a piece of the residue in a series of aqueous solutions. Twenty-one solutions of different densities were prepared, covering a range from 0.900 to 1.100 g/cm³ in increments of 0.01 g/cm³. The solutions with densities less than water were made using methanol and water; the baths with densities greater than water were prepared with sodium chloride and water. Each residue sample was first placed in the lowest density solution (i.e., 0.900 g/cm³). If the residue floated in this solution, it meant that the density of the residue was less than 0.900 g/cm³, and was noted as such in the results. If the residue sank in this solution, it meant that the density of the residue was greater than 0.900 g/cm³. These samples were then placed in solutions of higher densities until one was found in which they floated. Soot samples were also taken during the residue burns to quantify the smoke yield for each crude oil.

3. Amoco High Island Crude Oil

Amoco High Island (AHI) crude oil is produced by Amoco Corporation in the Texas sector of the Gulf of Mexico. AHI is a light crude oil (density of 0.815 g/cm³ at 20°C), resembling a condensate in many respects, with a low viscosity and density, and a high volatility. AHI was the lightest of the oils tested.

3.1 Evaporation

The percentage of oil evaporated in the wind tunnel corresponding to 8 and 27 hours of exposure to the hypothetical spill conditions is presented in Table 3-1. Also shown is the percentage of oil removed by sparging.

Table 3-1: Results of Evaporation Tests

Duration of Exposure* (hr)	Evaporation in Wind Tunnel (wt. %)	Evaporation by Sparging (wt. %)
8	33.4	33.1
27	38.5	37.9

*hypothetical spill conditions: 2-mm thick slick, 24°C, 2.5 m/s wind speed.

3.2 Emulsion Formation-Tendency and Stability

The emulsion formation-tendency and stability indices for AHI crude oil are given in Table 3-2. Raw data for the emulsion formation-tendency and stability tests can be found in Appendix 1.

Table 3-2: Results of Emulsion Formation Tests

Evaporation (wt. %)	Formation-Tendency Index	Stability Index
0	0	0
33.1	0.13	0.1

Amoco High Island crude oil only forms an emulsion after it has been weathered considerably; the emulsions are not stable and will break quickly after the mixing energy is removed.

3.3 Emulsion Breaker Effectiveness

The results of the emulsion breaker effectiveness test are presented in Table 3-3. The dehydration achieved is shown for both the 1:500 and 1:5000 demulsifier to emulsion ratios. The test was not performed on the 33.1% evaporated crude because it did not show a tendency to form an emulsion (see Section 3.2). Raw data for the emulsion breaker effectiveness test is in Appendix 2.

Table 3-3: Results of Emulsion Breaker Effectiveness Tests

Evaporation (wt. %)	Emulsion Breaker	Dehydration _{1M} (vol. %)		Dehydration _{24hr} (vol. %)	
		1:500	1:5000	1:500	1:5000
37.9	Alcopol	93	93	93	93
	Brexit	93	85	93	89
	EXO	85	85	89	89
	Control	0		0	

All emulsion breakers worked quickly and well with the AHI crude oil, even at the 1:5000 ratio. The control emulsion did not break. Brexit was chosen for use in the emulsion breaking burns.

3.4 Baseline Burns

Table 3-4 presents the results of the baseline burn tests with AHI crude oil. Raw data for the baseline burn tests can be found in Appendix 3.

The AHI crude oil burned very well. Ignition was achieved using only gelled gasoline for all emulsions except the 60% water, 37.9% evaporated crude. The burn rate was steady (between 1 and 1.5 mm/min) and burn efficiency was always high. This was due, in part, to the fact that the emulsions formed were not very stable and broke easily when heated. As expected, burn efficiency declined slightly as the emulsified water content was increased.

Table 3-4: Results of Baseline Burn Tests

Evap. (wt. %)	Water Content (vol. %)	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)
0	0	2073	172	1.4	92
0	25	2093	131	1.4	91
0	33	2256	120	1.3	92
0	50	2277	125	1.5	87
0	60	Emulsion was not stable.			
33.1	0	2361	186	1.2	92
33.1	25	2268	139	1.0	91
33.1	33	2307	160	1.1	89
33.1	50	2333	152	1.1	86
33.1	60	2588	145	1.4	86
37.9	25	2255	85	1	95
37.9	33	2289	137	1	91
37.9	50	2411	211	1	81
37.9	60	Emulsion was not ignitable with gelled gasoline.			

The 60% water emulsion of the fresh AHI was not stable, so it was not used in the burn testing. The fact that AHI ignited easily meant that many burns were performed. The high degree of evaporation reached by AHI in the wind tunnel (37.9%) required that several 20-L batches be sparged to get enough oil for all of the burn tests. To be sure that the oil didn't run out before all tests had been completed, it was decided to skip the 0% water baseline burn of the 37.9% AHI. It is certain that this slick would have burned.

3.5 Emulsion Breaker Burns

Brexit was used for the emulsion breaker burn with AHI crude oil. Only the 37.9% evaporated, 60% water emulsion was not ignitable with gelled gasoline and so required demulsifier for ignition. Table 3-5 presents the results of this burn. The raw data for the emulsion breaker burns can be found in Appendix 4.

Table 3-5: Results of Emulsion Breaker Burn

Evap. (wt. %)	Water Content (vol. %)	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)
37.9	60	2517	175	1.2	82

Brexit was effective in breaking and allowing the ignition of the AHI crude oil emulsion. The burn rate of the treated emulsion was higher than that of the untreated emulsion.

3.6 Burns in Waves

Since the 60% water emulsion of the fresh AHI was not stable, it was decided to test the effect of waves with a 50% water content emulsion instead. For the other two degrees of evaporation, 60% water emulsions were tested. Table 3-6 presents the results of the burns with AHI in waves. The raw data for these burns can be found in Appendix 5.

Table 3-6: Results of burns in waves with AHI emulsions

Evap. (wt. %)	Water Content (vol. %)	Wave Setting	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)
0	50	none	2277	125	1.5	87
0	50	low	2481	122	1.6	90
0	50	high	2423	93	1.5	92
33.1	60	none	2588	145	1.4	86
33.1	60	low	2401	180	1.1	79

33.1	60	high	2404	180	1.3	79
37.9*	60	none	2517	175	1.2	82
37.9*	60	low	2486	130	1.2	86
37.9*	60	high	2527	258	1.5	74

*5 mL of Breaxit was added, followed by 2 minutes of mixing and 40 minutes of settling prior to ignition

The waves did not have a significant effect on the burn characteristics of AHI crude. This is likely because the oil is very flammable to begin with, thus it burns well in all the test conditions.

3.7 Residue Burns

The results of the residue burn tests are presented in Table 3-7. The raw data for these tests can be found in Appendix 6.

Table 3-7: Results of Residue Burn Tests

Slick Thickness (mm)	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)	Residue Density (g/cm₃)	Soot Yield (g soot/kg fuel)
50	5223	168	1.3	97	0.925	38.4
100	10435	730	1.3	93	0.935	25.5

The residue of thick burns of AHI crude oil will not likely sink.

3.8 Conclusions

Amoco High Island crude oil is an excellent candidate for *in situ* burning. It is easy to ignite, even at high degrees of evaporation and with high percentages of emulsified water. Furthermore, the residue of a thick burn of AHI will not sink.

4. Carpinteria Crude Oil

Carpinteria is produced by Torch Operating Company in California. It is a medium crude oil (density of 0.910 g/cm³ at 20°C).

4.1 Evaporation

The percentage of oil evaporated in the wind tunnel corresponding to 8 and 27 hours of exposure to the hypothetical spill conditions is presented in Table 4-1. Also shown is the percentage of oil removed by sparging.

Table 4-1: Results of Evaporation Tests

Duration of Exposure* (hr)	Evaporation in Wind Tunnel (wt. %)	Evaporation by Sparging (wt. %)
8	10.3	10.3
27	16.2	15.9

*hypothetical spill conditions: 2-mm thick slick, 24°C, 2.5 m/s wind speed

4.2 Emulsion Formation-Tendency and Stability

The emulsion formation-tendency and stability indices for Carpinteria crude oil are presented in table 4-2. Raw data for the emulsion formation-tendency and stability tests is in Appendix 1.

Table 4-2: Results of Emulsion Formation Test

Evaporation (wt. %)	Formation-Tendency Index	Stability Index
0	1	1
10.3	1	1
15.9	1	1

Carpinteria crude oil readily forms stable emulsions at all degrees of evaporation.

4.3 Emulsion Breaker Effectiveness

The results of the emulsion breaker effectiveness tests are presented in Table 4-3. The dehydration achieved with each chemical is shown for both the 1:500 and 1:5000 demulsifier to emulsion ratios. Raw data for the emulsion breaker effectiveness test can be found in Appendix 2.

Table 4-3: Results of Emulsion Breaker Effectiveness Test

Evaporation (wt. %)	Emulsion Breaker	Dehydration _{1M} (vol. %)		Dehydration _{24hr} (vol. %)	
		1:500	1:5000	1:500	1:5000
10.3	Alcopol	85	0	85	0
	Brexit	58	4	58	4
	EXO	23	31	31	31
	Control		0		0
15.9	Alcopol	70	0	70	0
	Brexit	?	0	62	0
	EXO	4	0	8	0
	Control		0		0

*emulsion coated the walls of the fleaker, which made discerning the water/oil interface impossible

No increase in dehydration was noted after the initial reading (2 minutes). Alcopol was clearly the best emulsion breaker for Carpinteria crude oil, with Brexit coming second and EXO performing the worst. None of the emulsion breakers were effective at the 1:5000 demulsifier to emulsion ratio. Alcopol was used for the Emulsion Breaker burns. The control emulsion did not break.

4.4 Baseline Burns

Table 4-4 presents the results of the baseline burn tests with Carpinteria crude oil. Raw data for the baseline burn tests can be found in Appendix 3.

Table 4-4: Results of Baseline Burn Tests

Evap. (wt. %)	Water Content (vol. %)	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)
0	0	2288	183	1.1	92
0	25	Not ignitable with gelled gasoline.			
10.3	0	2406	293	1.0	88
15.9	0	2440	224	1	91

The emulsions of Carpinteria produced with the gear pump were extremely stable. Only the 0% water burns were ignited successfully with gelled gas, although these did burn efficiently.

4.5 Emulsion Breaker Burns

Alcopol was used for the emulsion breaker burn with Carpinteria crude oil. Table 4-5 presents the results of this burn. The raw data can be found in Appendix 4.

Table 4-5: Results of Emulsion Breaker Burn Test

Evap. (wt. %)	Water Content (vol. %)	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)
0	25	Not ignitable with either gelled gasoline or fresh crude.			

The Alcopol did not allow the ignition of the 25% water emulsion of fresh Carpinteria. No further emulsion breaker burns were conducted.

4.6 Burns in Waves

Since the emulsions made from Carpinteria were not ignitable, even with emulsion breaker, only the unemulsified oil was used in the wave burn tests. Table 4-6 presents the results of the burns in waves with Carpinteria. The raw data for the burns in waves can be found in Appendix 5.

Table 4-6: Results of Burns in Waves

Evap. (wt. %)	Water Content (vol. %)	Wave Setting	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)
0	0	none	2288	183	1.1	92
0	0	low	2350	168	1.3	93
0	0	high	2235	168	1.7	93
10.3	0	none	2406	293	1.0	88
10.3	0	low	2429	154	1.2	94
10.3	0	high	2353	580	1.0	75
15.9	0	none	2440	224	1.0	91
15.9	0	low	2450	295	1.0	88
15.9	0	high	2424	580	1.0	76

The waves did not have a significant effect on the burning of Carpinteria; although, the high waves did cause a slight reduction in burn efficiency for the two weathered burns. That said, the fresh Carpinteria did show an increased burn rate at the high wave setting, and the intense burn phase was noticeably less pronounced for the 10.3% evaporated Carpinteria with high waves, than for the other two burns with this oil.

4.7 Residue Burns

The results of the residue burn tests are presented in Table 4-7. The raw data for these tests can be found in Appendix 6.

Table 4-7: Results of Residue Burn Tests

Slick Thickness (mm)	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)	Residue Density (g/cm₃)	Soot Yield (g soot/kg fuel)
50	5686	870	1.3	85	1.020	40.8
100	11592	1210	1.2	90	1.000	32.7

The residue of thick burns of Carpinteria crude oil may sink when they cool, depending on the thickness of the slick. The phenomenon of density reaching a maximum and then decreasing, as the slick thickness is increased, has been noted before and may be related to the vigorous burn phase (Buist et al., 1995).

4.8 Conclusions

In situ burning is only suitable for Carpinteria crude oil if the response can be initiated before the oil emulsifies. Evaporation does not seem to hinder ignition, but an emulsified water content greater than 25% will prevent it. The residue may sink as it cools depending (largely) on the initial thickness of the slick.

5. Green Canyon Crude Oil

Green Canyon Block 65 (Green Canyon) is produced by Shell Offshore Inc. in the Gulf of Mexico. It is a medium crude oil (density of 0.880 g/cm³ at 20°C).

5.1 Evaporation

The percentage of oil evaporated in the wind tunnel corresponding to 8 and 27 hours of exposure to the hypothetical spill conditions is presented in Table 5-1. Also shown is the percentage of oil removed by sparging.

Table 5-1: Results of Evaporation Tests

Duration of Exposure* (hr)	Evaporation in Wind Tunnel (wt. %)	Evaporation by Sparging (wt. %)
8	15.2	15.9
27	19.9	19.4

*hypothetical spill conditions: 2-mm thick slick, 24°C, 2.5 m/s wind speed

5.2 Emulsion Formation-Tendency and Stability

The emulsion formation-tendency and stability indices for Green Canyon crude oil are presented in table 5-2. The raw data for these tests can be found in Appendix 1.

Table 5-2: Results of Emulsion Formation Tests

Evaporation (wt. %)	Formation-Tendency Index	Stability Index
0	1	0
15.9	1	0.1
19.4	1	1

Green Canyon crude oil readily formed emulsion at all degrees of evaporation; the emulsions were only stable at the highest degree of evaporation.

5.3 Emulsion Breaker Effectiveness

The results of the emulsion breaker effectiveness test are presented in Table 5-3. The dehydration achieved is shown for both the 1:500 and 1:5000 demulsifier to emulsion ratios. Raw data for the emulsion breaker effectiveness test can be found in Appendix 2.

Table 5-3: Results of Emulsion Breaker Test

Evaporation (wt. %)	Emulsion Breaker	Dehydration _{1M} (vol. %)		Dehydration _{24hr} (vol. %)	
		1:500	1:5000	1:500	1:5000
15.9	Alcopol 070 PG	89	27	97	66
	Brexit OEB-9	70	43	85	58
	EXO-0894	31	31	70	39
	Control	0		0	
19.4	Alcopol 070 PG	89	81	93	81
	Brexit OEB-9	70	66	81	74
	EXO-0894	47	43	81	85
	Control	0		0	

Alcopol was the best emulsion breaker for Green Canyon crude oil, with Brexit coming second and EXO performing the worst. Alcopol was used for the Emulsion Breaker burns. There was typically an increase in dehydration between the first reading (2 minutes) and the reading after 24 hours. The control emulsion did not break.

5.4 Baseline Burns

Table 5-4 presents the results of the baseline burn tests with Green Canyon crude oil. The raw data can be found in Appendix 3.

Table 5-4: Results of Baseline Burns

Evap. (wt. %)	Water Content (vol. %)	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)
0	0	2203	188	1.2	92
0	25	Not ignitable with gelled gasoline.			
15.9	0	2380	150	0.9	94
19.4	0	2351	689	0.8	71

The emulsions of Green Canyon made with the gear pump were extremely stable. Only the 0% water burns were ignited successfully with gelled gas, although these did burn efficiently.

5.5 Emulsion Breaker Burns

Alcopol was used for the emulsion breaker burns with Green Canyon crude oil. Table 5-5 presents the results of these burns. The raw data can be found in Appendix 4.

Table 5-5: Results of Emulsion Breaker Burn

Evap. (wt. %)	Water Content (vol. %)	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)
0	25	2371	737	0.4	57
0	33	Not ignitable with either gelled gasoline or fresh crude.			

The Alcopol allowed the ignition of the 25% water emulsion of fresh Green Canyon, but not that of the 33% water emulsion. No further emulsion breaker burns were conducted with Green Canyon crude oil. The 25% water emulsion burned particularly slowly and complete ignition of the slick surface took 11 minutes (compared with instant ignition for the 0% water burn).

5.6 Burns in Waves

Since all but the fresh, 25% water emulsion of Green Canyon were not ignitable, even with emulsion breaker, it was the only emulsion used in the wave burn tests. Table 5-6 presents the results of the burns in waves with Green Canyon. The raw data for the burns in waves can be found in Appendix 5.

Table 5-6: Results of Burns in waves

Evap. (wt. %)	Water Content (vol. %)	Wave Setting	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)
0	0	none	2206	188	1.2	92
0	0	low	2299	684	1.1	70
0	0	high	2254	225	1.6	90
15.9	0	none	2380	150	0.9	94
15.9	0	low	2463	180	1.1	93
15.9	0	high	2365	185	1.4	92
19.4	0	none	2351	689	0.8	71
19.4	0	low	2396	160	1.1	93
19.4	0	high	2392	148	1.5	94

The waves had did not have a large effect on the burning of unemulsified Green Canyon. All of the burns were efficient. The burn rates showed slight increases at the high wave setting over those of the calm and low burns in waves.

The 25% water emulsion of the fresh oil was tested with emulsion breaker in low waves, but with no pre-mixing of the breaker into the slick. The only mixing energy was supplied by the waves. Table 5-7 presents the results of this test.

Table 5-7: Results of Emulsion Breaker Burn in Waves

Evap. (wt. %)	Water Content (vol. %)	Wave Setting	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)
0	25	low	2325	133	0.7	92

The burn was successful, indicating that if *in situ* burning is used on a Green Canyon emulsion, it may be possible to simply spray on the emulsion breaker for it to be effective.

5.7 Residue Burns

The results of the residue burn tests are presented in Table 5-8. The raw data for these tests can be found in Appendix 6.

Table 5-8: Results of Residue Burn Tests

Slick Thickness (mm)	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)	Residue Density (g/cm₃)	Soot Yield (g soot/kg fuel)
50	6134	380	1.1	94	1.030	36.9
100	10465	570	1.1	95	1.000	25.2

The residue of thick burns of Green Canyon crude oil may sink when it cools, depending on the initial thickness of the slick.

5.8 Conclusions

In situ burning is only suitable for Green Canyon crude oil if the response can be initiated before the oil emulsifies. Evaporation does not seem to hinder ignition, but an emulsified water content greater than 25% may prevent. The residue may sink as it cools depending (largely) on the initial thickness of the slick.

6. Santa Clara Crude Oil

Santa Clara crude oil is produced by Chevron U.S.A., in California. It is a heavy, waxy crude oil (density of 0.932 g/cm³ at 20°C), characterized by a very strong sulphur smell.

6.1 Oil Evaporation

The percentage of oil evaporated in the wind tunnel corresponding to 8 and 27 hours of exposure to the hypothetical spill conditions is presented in Table 6-1. Also shown is the percentage of oil removed by sparging.

Table 6-1: Results of Evaporation Tests

Duration of Exposure* (hr)	Evaporation in Wind Tunnel (wt. %)	Evaporation by Sparging (wt. %)
8	7.7	8.0
27	12.4	13.5

*hypothetical spill conditions: 2-mm thick slick, 24°C, 2.5 m/s wind speed

6.2 Emulsion Formation-Tendency and Stability

The emulsion formation-tendency and stability indices for Santa Clara crude oil are presented in table 6-2. The raw data for these tests can be found in Appendix 1.

Table 6-2: Results of Emulsion Formation Test

Evaporation (wt. %)	Formation-Tendency Index	Stability Index
0	1	1
8.0	1	1
13.5	1	1

Santa Clara crude oil readily forms stable emulsion at all degrees of evaporation.

6.3 Emulsion Breaker Effectiveness

The results of the emulsion breaker effectiveness tests are presented in Table 6-3. The dehydration achieved is shown for both the 1:500 and 1:5000 demulsifier to emulsion ratios. The fresh and evaporated Santa Clara crude oil was too viscous to pump, so the emulsions were made using an electric drill with a paint mixing attachment. Raw data for the emulsion breaker effectiveness test can be found in Appendix 2.

Table 6-3: Results of Emulsion Breaker Effectiveness Test

Evaporation (wt. %)	Emulsion Breaker	Dehydration _{IM} (vol. %)		Dehydration _{24hr} (vol. %)	
		1:500	1:5000	1:500	1:5000
8.0	Alcopol	31	0	43	8
	Brexit	0	0	31	12
	EXO	12	0	35	16
	Control	0		0	
13.5	Alcopol	0	0	0	8
	Brexit	0	0	0	8
	EXO	0	0	8	4
	Control	0		0	

The Santa Clara crude oil emulsions were very stable and none of the emulsion breakers worked well, especially with the 13.5% evaporated sample. There was almost no dehydration with any of the demulsifiers at the 1:5000 application ratio. Alcopol was chosen as the best for use in the emulsion breaker burns. The control emulsions did not break.

6.4 Baseline Burns

Table 6-4 presents the results of the baseline burn tests with Santa Clara crude oil. Again, the Santa Clara was too viscous to use the gear pump and the emulsions were made using a drill with a paint mixing attachment. The raw data for these tests can be found in Appendix 3.

Table 6-4: Results of Baseline Burn Tests

Evap. (wt. %)	Water Content (vol. %)	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)
0	0	2372	213	1.4	91
0	25	Not ignitable with either gelled gasoline or fresh oil.			
8.0	0	2380	180	1.1	92
13.5	0	2436	230	1.4	91

The Santa Clara emulsions were very stable, and only the 25% water emulsion of the fresh oil was not ignitable, even with a 2-mm layer of fresh crude. Only the unemulsified oils were ignitable, although these burned well.

6.5 Emulsion Breaker Burns

Alcopol was used for the emulsion breaker burn with Santa Clara crude oil. Table 6-5 presents the results of this burn. The raw data can be found in Appendix 4.

Table 6-5: Results of Emulsion Breaker Burn Tests

Evap. (wt. %)	Water Content (vol. %)	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)
0	25	Not ignitable with either gelled gasoline or fresh crude			

Not even the addition of emulsion breaker allowed the ignition of the fresh 25% water emulsion.

6.6 Burns in Waves

Since all of the Santa Clara emulsions were not ignitable, even with emulsion breaker, only the unemulsified oil was used in the wave burn tests. Table 6-6 presents the results of the burns in waves with Santa Clara. The raw data for the burns in waves can be found in Appendix 5.

Table 6-6: Results of Burns in Waves

Evap. (wt. %)	Water Content (vol. %)	Wave Setting	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)	
0	0	none	2372	213	1.4	91	
0	0	low	2368	170	1.7	93	
0	0	high	2401	391	2.0	84	
8.0	0	none	2380	180	1.1	92	
8.0	0	low	2434	260	1.7	89	
8.0	0	Not enough evaporated oil to conduct burn.					
13.5	0	none	2436	230	1.4	91	
13.5	0	low	2468	290	1.6	88	
13.5	0	high	2473	365	2.3	85	

The waves did not have a large effect on the burn characteristics of Santa Clara. The burn efficiency was unaffected by the waves, while the burn rate showed a slight increase.

6.7 Residue Burns

Not enough fresh Santa Clara was available to perform the 100-mm thick residue burn. The result of the 50-mm thick residue burn test is presented in Table 6-7. The raw data for this test can be found in Appendix 6.

Table 6-7: Results of Residue Burn Tests

Slick Thickness (mm)	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)	Residue Density (g/cm ₃)	Soot Yield (g soot/kg fuel)
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The residue of thick burns of Santa Clara crude oil will sink in both salt and fresh water. If an *in situ* burn is conducted, care must be taken to collect the residue soon after the burn is finished, before the residue cools and sinks.

6.8 Conclusions

In situ burning is only suitable for Santa Clara crude oil if the burn can be initiated before the oil emulsifies. Evaporation does not hinder ignition, but an emulsified water content greater than 25% will prevent it. The residue may sink as it cools depending (largely) on the initial thickness of the slick.

7. Santa Ynez Crude Oil

Santa Ynez is produced by Exxon U.S.A. in California. It is a heavy crude oil (density of 0.955 g/cm³ at 20°C), characterized by a strong sulphur smell, and was the heaviest oil tested.

7.1 Evaporation

The percentage of oil evaporated in the wind tunnel corresponding to 8 and 27 hours of exposure to the hypothetical spill conditions is presented in Table 7-1. Also shown is the percentage of oil removed by sparging.

Table 7-1: Results of Evaporation Tests

Duration of Exposure* (hr)	Evaporation in Wind Tunnel (wt. %)	Evaporation by Sparging (wt. %)
8	5.9	6.3
27	9.6	11.4

*hypothetical spill conditions: 2-mm thick slick, 24°C, 2.5 m/s wind speed

7.2 Emulsion Formation-Tendency and Stability

The Formation-Tendency and Emulsion Stability indices for Santa Ynez crude oil are presented in table 7-2. The raw data for these tests can be found in Appendix 1.

Table 7-2: Results of Emulsion Formation Test

Evaporation (wt. %)	Formation-Tendency Index	Stability Index
0	1	1
6.3	1	1
11.4	1	1

Santa Ynez crude oil readily forms stable emulsion at all degrees of evaporation.

7.3 Emulsion Breaker Effectiveness

The results of the emulsion breaker effectiveness test is presented in Table 7-3. The oil was too viscous pump, so the emulsions were made using an electric drill with a paint mixing attachment. The raw data for these tests can be found in Appendix 2.

Table 7-3: Results of Emulsion Breaker Tests

Evaporation (wt. %)	Emulsion Breaker	Dehydration _{IM} (vol. %)		Dehydration _{24hr} (vol. %)	
		1:500	1:5000	1:500	1:5000
6.3	Alcopol	23	19	58	23
	Breaxit	8	12	31	12
	EXO	27	8	31	19
	Control		0		8
11.4	Alcopol	0	0	19	8
	Breaxit	0	0	12	19
	EXO	4	0	19	23
	Control		0		0

The Santa Ynez emulsions were very stable and none of the emulsion breakers worked very well, particularly at the higher degree of evaporation. Alcopol was chosen for the emulsion breaker burns. The control emulsion for the 6.3% evaporated Santa Ynez crude oil broke slightly (8% dehydration) after 24 hours of settling. The control emulsion for the 11.4% evaporated Santa Ynez crude oil was stable.

7.4 Baseline Burns

Table 7-4 presents the results of the baseline burn tests with Santa Ynez crude oil. The raw data for this test can be found in Appendix 3.

Table 7-4: Results of Baseline Burns

Evap. (wt. %)	Water Content (vol. %)	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)
0	0	Not ignitable with gelled gasoline.			

It was surprising that not even the fresh Santa Ynez could be ignited. A sample of the oil was subjected to a Karl-Fischer titration to determine its water content. It turned out that there was 30% (wt. %) water already in the oil. Apparently the sample of Santa Ynez received had been taken before the de-watering stage of processing. Ignition of the fresh oil was attempted a second time after adding 5 mL of Alcopol, mixing it for 2 minutes and allowing it to settle for 40 minutes. The attempt was unsuccessful.

No further burn tests were attempted with Santa Ynez.

7.5 Conclusions

In situ burning would not be a suitable response for spills of Santa Ynez crude oil.

The sample that was received had a water content of about 30%, right out of the drum. The sample must have been taken before the de-watering stage of the refining and production process. It would be useful to speak with someone at the production facility to determine whether there is a possibility that a spill might occur after the de-watering process. If so, it would be worthwhile to obtain a de-watered sample and conduct the same *in situ* burning suitability tests. It is possible that the de-watered Santa Ynez would be better suited to *in situ* burning.

8. West Delta Crude Oil

West Delta Block 30 (West Delta) crude oil is produced by Exxon U.S.A. in the Louisiana sector of the Gulf of Mexico. It is a medium crude oil (density of 0.915 g/cm³ at 20°C).

8.1 Evaporation

The percentage of oil evaporated in the wind tunnel corresponding to 8 and 27 hours of exposure to the hypothetical spill conditions is presented in Table 8-1. Also shown is the percentage of oil removed by sparging.

Table 8-1: Results of Evaporation Tests

Duration of Exposure* (hr)	Evaporation in Wind Tunnel (wt. %)	Evaporation by Sparging (wt. %)
8	7.4	7.3
27	11.2	11.4

*hypothetical spill conditions: 2-mm thick slick, 24°C, 2.5 m/s wind speed

8.2 Emulsion Formation-Tendency and Stability

The Formation-Tendency and Emulsion Stability indices for West Delta crude oil are presented in table 8-2. The raw data for these tests can be found in Appendix 1.

Table 8-2: Results of Emulsion Formation Test

Evaporation (wt. %)	Formation-Tendency Index	Stability Index
0	1	1
7.3	1	1
11.4	1	1

The tests indicate that West Delta crude oil readily forms stable emulsions even when fresh.

8.3 Emulsion Breaker Effectiveness

The results of the emulsion breaker effectiveness tests are presented in Table 8-3. The dehydration achieved is shown for both the 1:500 and 1:5000 demulsifier to emulsion ratios. Raw data for the emulsion breaker effectiveness test can be found in Appendix 2.

Table 8-3: Results of Emulsion Breaker Test

Evaporation (wt. %)	Emulsion Breaker	Dehydration _{IM} (vol. %)		Dehydration _{24hr} (vol. %)	
		1:500	1:5000	1:500	1:5000
7.3	Alcopol	97	89	97	89
	Breaxit	97	81	97	97
	EXO	74	50	97	97
	Control		0		12
11.4	Alcopol	89	81	97	97
	Breaxit	78	70	93	93
	EXO	58	47	93	93
	Control		0		0

All emulsion breakers worked well with the West Delta crude oil, even at the 1:5000 ratio. It was decided to use EXO for the Emulsion breaking burns since it's performance was comparable to the other emulsion breakers but it had not yet been selected for burns with emulsion breakers. The control emulsion of the 7.3% evaporated West Delta crude oil broke slightly after 24 hours (12 percent of the water dropped out of the emulsion). The control emulsion for the 11.4% evaporated West Delta crude oil was stable.

8.4 Baseline Burns

Table 8-4 presents the results of the baseline burn tests with West Delta crude. Raw data from these tests can be found in Appendix 3.

Table 8-4: Results of Baseline Burns

Evap. (wt. %)	Water Content (vol. %)	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)
0	0	2307	142	1.4	94
0	25	Not ignitable with gelled gasoline.			
7.3	0	2333	210	1.2	91
11.4	0	2368	150	1.3	94

The emulsions of West Delta were stable. Only the unemulsified oils were ignitable with gelled gasoline.

8.5 Emulsion Breaker Burns

EXO was used for the emulsion breaker burns with West Delta crude oil. Table 8-5 presents the results of this burn. The raw data for these tests can be found in Appendix 4.

Table 8-5: Results of Emulsion Breaker Burn Tests

Evap. (wt. %)	Water Content (vol. %)	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)
0	25	2407	606	0.8	66
0	33	2396	668	0.7	57
0	50	2484	600	0.7	50
0	60	2465	174	0.8	81
7.3	25	2435	749	0.7	58
7.3	33	2416	1400	0.2	11
7.3	50	2428	210	0.5	82
7.3	60	Not ignitable with gelled gasoline.			

11.4	25	2360	1000	0.3	42
11.4	33	2411	1100	0.3	30
11.4	50	2511	763	0.4	38
11.4	60	2601	554	0.5	48

Few of the West Delta emulsions burned efficiently, although almost all were ignitable with gelled gasoline or 2 mm of fresh oil. The presence of emulsified water dramatically decreases the burn efficiency of West Delta, even when emulsion breakers are used.

8.6 Burns in Waves

Table 8-6 presents the results of the wave burn tests with West Delta.

Table 8-6: Results of Burns in Waves

Evaporation (wt. %)	Water Content (vol. %)	Wave Setting	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)
0	0	none	2307	142	1.4	94
0	0	low	2418	172	1.4	90
0	0	high	2421	198	1.8	92
0	60	none	2465	174	0.8	81
0	60	low	2517	125	0.9	87
0	60	high	2608	330	1.3	69
7.3	0	none	2333	210	1.2	91
7.3	0	low	2363	225	1.5	91
7.3	0	high	2360	474	1.9	80
7.3	60	none	Not ignitable with gelled gasoline.			
7.3	60	low	2517	125	0.9	87
7.3	60	high	Emulsion dispersed out of ring during 40 min settling period.			
11.4	0	none	2368	150	1.3	94
11.4	0	low	2380	320	1.7	87

11.4	0	high	2316	487	1.9	79
11.4	60	none	2601	554	0.5	48
11.4	60	low	2563	175	1.1	83
11.4	60	high	Emulsion dispersed out of ring during 40 min settling period.			

Since the other heavy and medium crude oils were difficult to burn and few burns in waves were performed with emulsions, extra burns in waves were done with West Delta. The raw data can be found in Appendix 5.

The presence of waves did not have a large effect on the burning of West Delta, although there was an increase in burn rate with the increased wave action. The 60% water emulsions of the two evaporated West Delta samples dispersed out of the ring during the high wave test mixing periods. This has been seen before with previous experiments. It is due to a combination of the high water content, which increases the density of the emulsion so that it is less buoyant, and the presence of emulsion breaking surfactant, which enhances the dispersion of the emulsion.

Additional burns in waves were performed with West Delta emulsions and emulsion breakers, but with no pre-mixing. The only mixing energy was supplied by wave action. 60% water emulsions were tested. Table 8-7 presents the results.

Table 8-7: Results of Burns in Waves with Emulsion Breaker

Evaporation (wt. %)	Water Content (vol. %)	Wave Setting	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)
0	60	low	2564	127	0.8	88
7.3	60	low	2361	237	0.7	71
11.4	60	low	2480	343	0.6	63

All three burns were successful indicating that if *in situ* burning is used on a West Delta emulsion, it may be possible to simply spray on the emulsion breaker for it to be effective.

8.7 Residue Burns

The results of the residue burn tests are presented in Table 8-8. The raw data for these tests can be found in Appendix 6.

Table 8-8: Results of Residue Burn Tests

Slick Thickness (mm)	Initial Mass (g)	Residue Mass (g)	Burn Rate (mm/min)	Burn Efficiency (%)	Residue Density (g/cm₃)	Soot Yield (g soot/kg fuel)
50	5855	108	1.3	98	1.075	41.6
100	11686	90	1.4	99	1.030	44.6

The residue of thick burns of West Delta crude oil will sink in both salt and fresh water once cooled.

8.8 Conclusions

In situ burning would be a suitable response option for spills of West Delta crude oil. Emulsion breakers could be used to extend the window of opportunity for burning if the oil is emulsified. The residue may sink as it cools depending (largely) on the initial thickness of the slick.

9. Conclusions and Recommendations

The results of the in situ burning tests for each oil are summarized in Table 9-1.

Table 9-1: Summary of Test Results

Crude Oil	Amenable to <i>In Situ</i> Burning?	Could Residue Sink?	Forms Emulsion?	Best Emulsion Breaker
High Island	yes	unlikely	when highly weathered	all worked well
Carpinteria	if response initiated before emulsification	possible	when fresh	Alcopol
Green Canyon	if response initiated before emulsification	possible	when fresh	Alcopol
Santa Clara	if response initiated before emulsification	likely	when fresh	all worked poorly
Santa Ynez	no	unknown	when fresh	all worked poorly
West Delta	yes	likely	when fresh	all worked well

The stability of a water-in-oil emulsion and its response to emulsion breakers is highly dependent on the properties of the oil. Only three of the more widely available emulsion breakers were tested on the oils in this study. It is likely that there are other emulsion breakers being marketed that would perform as well or better on some of the oils. It would be worthwhile to pursue testing with other emulsion breakers for those oils that were difficult to break (i.e., Carpinteria, Green Canyon Block 65, Santa Clara and Santa Ynez).

This study has shown that *in situ* burning is not a suitable response option for all oils. It is vital that this work be continued and other oils tested to establish a catalogue of oils and their *in situ* burning related properties. This must be done before *in situ* burning can be considered for use at an actual spill.

10. References

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Appendix 1

Data for Emulsion Formation-Tendency and Stability Tests

Appendix 2

Data for Emulsion Breaker Effectiveness Tests

Appendix 3

Data for Baseline Burn Tests

Appendix 4

Data for Emulsion Breaker Burn Tests

Appendix 5

Data for Wave Burn Tests

Appendix 6

Data for Residue Burn Tests