Laboratory Studies of the Properties of In-Situ Burn Residues

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LIST OF ABBREVIATIONS, SYMBOLS, AND ACRONYMS

Term	Abbreviation, Symbol, or Acronym
Alaska North Slope	ANS
Alberta Sweet Mixed Blend	ASMB
Equilibrium Flash Vaporization	EFV
American Society for Testing and Materials	ASTM
Boiling Point	BP
Initial Boiling Point	IBP
Fluorescence Indicator Absorption	FIA
Bauxite Silica Gel	BSG
Saturates, Aromatics, Resins, Asphaltenes	SARA
Gas Chromatographic	GC
Not Measured	N/M
Parts per Thousand	PPT
Analog to Digital	A/D
Polynuclear Aromatic Hydrocarbon	PAH

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Laboratory Studies of the Properties of In-Situ Burn Residues

Abstract

This study investigated the physical and chemical properties of the residue from in-situ burns of oil. It involved burning small slicks of oil on water, collecting samples of the residue after natural extinction of the fire, then analyzing the properties of the residues. The residue properties were compared to the original oil's properties.

Eight oils were selected for the project. These were:

- i) Alaska North Slope crude
- ii) Alberta Sweet Mixed Blend crude
- iii) Arabian Heavy crude
- iv) Arabian Light crude
- v) Bonny Light crude
- vi) Iranian Heavy crude
- vii) Mayan crude
- viii) automotive diesel

Test burns were conducted using samples of all eight oils when fresh and unweathered. In addition, two of the crude oils (Mayan and Arabian Light) were artificially weathered to investigate the effect of evaporation on burn residue properties.

Burn experiments were carried out in the laboratory on salt water at room temperature (15°C). Three thicknesses of oil were burned: 5, 10 and 15 cm. The physical properties of the residue measured were: density (at two temperatures); and, (for samples with pour points below 45°C) water content; pour point; and, viscosity (at two temperatures). All unburned oils and residues were also chemically analyzed to provide the total fraction of saturates, aromatics, resins and asphaltenes in the samples.

The results show that the residues from thick slicks of heavier crudes may sink in salt water once they cool to ambient temperatures, that these residues have lost all of their volatile (boiling at less than 205°C) components and that the residues are semi-solid or solid at ambient temperatures. Efforts were made to correlate burn residue density with initial oil properties and burn parameters.

1.0 Introduction

Research conducted over the past 25 years on the use of in-situ burning as a marine oil spill countermeasure has resulted in a rapidly growing acceptance of the technique as an option for spill cleanup. In-situ burning has evolved from its beginnings as a tool for spill response in remote ice-covered waters to a technology that can be used in open water conditions almost anywhere to remove large volumes of oil contained in fire-resistant booms.

One source of concern with the use of in-situ burning has been the fate, properties and potential impacts of the residue remaining after a burn has extinguished. One important question has been whether the residue would sink. Studies of residues from meltpool-type burns (Energetex 1977 and 1980, Dickins and Buist 1981, Evans *et al.* 1986, Smith and Diaz 1987, Guenette *et al.* 1994) showed that, although the residue from in-situ burning was more dense and much more viscous than the original oil, it would not likely sink, even in fresh water. However, recent experiences that involved accidental burning on the sea of large volumes of heavy crude oils during actual spills (the *Haven* and the *Honam Jade* - Moller 1992, Turbini *et al.* 1993) and recent large-scale experiments involving thick slicks of moderately heavy crude oil contained in fire boom (Buist *et al.* 1995) have shown that burn residues can indeed sink.

The objective of the present study was to examine experimentally the factors that govern the physical and chemical properties of burn residue.

2.0 Theory

Figure 2.1 illustrates the major heat and mass transfer processes that occur during the in-situ burning of an oil slick on water. The key process is radiative heat transfer from the flame back to the surface of the slick. This heat is partially used by vaporizing the liquid hydrocarbons which then rise to mix with air above the slick and oxidize, or burn; the remainder transfers through the slick to the underlying water. Once ignited, a burning thick oil slick reaches a quasi-steady-state in which the vaporization rate sustains the necessary heat transfer back to the slick surface.

Extensive tests by Wakamiya *et al.* (1982) showed that the process by which the oil vaporizes is not a batch distillation (where the lightest, most volatile, components are boiled off from the entire slick first followed by progressively heavier, less volatile components), but is similar to an Equilibrium Flash Vaporization (EFV) in which vapor of essentially constant composition over time is produced by a feed of oil of essentially constant composition. Three observations lend credence to the EFV theory of in-situ combustion: (1) the surface temperatures of burning oil slicks remain relatively constant in the 200 to 300°C range during steady-state burning (Wakamiya *et al.* 1982, Evans *et al.* 1988, Guenette *et al.* 1994), if burning were a distillation the surface temperature of the slick would steadily increase; (2) a steep temperature profile exists in the burning slick (Wakamiya *et al.* 1982, Guenette *et al.* 1994), indicating a poorly-mixed oil layer, as required for EFV; and, (3) the presence of lighter ends in the oil residue remaining after a burn (i.e., Energetex 1977, Dome 1981, Wakamiya *et al.* 1982) which would not be present if in-situ burning was a distillation process. It is believed that EFV occurs during in-situ burning because the hot flames and the insulating characteristics of the oil combine to create high temperatures in a thin surface layer of the slick known as the "hot zone". This promotes near-complete vaporization of the surface of the oil slick with minimal mixing and heat transfer to the underlying oil and/or water layers.

It is clear that the vaporization process occurring during in-situ burning of crude oils is not a perfect EFV. It is well known that the burn residue, while still containing some lighter ends, differs markedly from the original crude. The residue's increased density and altered rheology strongly indicate that there is a progressive concentration of the very high molecular weight compounds in the remaining slick as in-situ burning proceeds. It is this concentration of heavy ends in the residue over time that may explain why residues from burns of relatively thin crude oil slicks (2 cm or less) do not sink while residues from burns of thick slicks of the same crude do sink. The concept of an imperfect EFV may also explain why burn residues of heavier crudes (which have greater initial concentrations of high molecular weight compounds) sink more readily than those of lighter crudes.

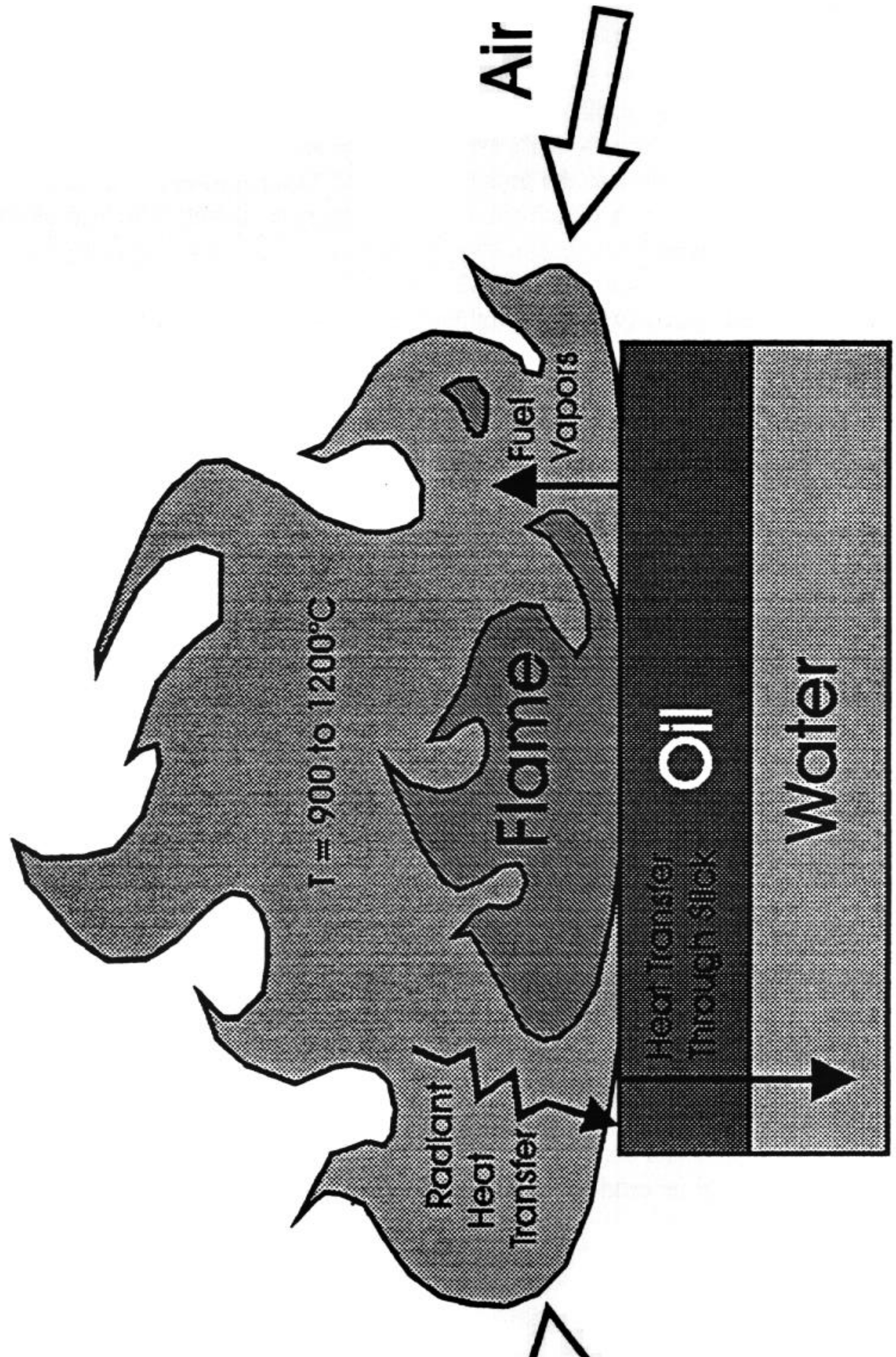

Figure 2.1 *Key heat and mass transfer processes in in-situ burning*

3.0 Methods

3.1 Test Oils

Eight oils, listed below, were selected for the project. These were representative of oils shipped by sea in North American waters, ones that have been involved in tankship fires that resulted in the residue sinking, or were used in recent in-situ burning field research studies.

i) Alaska North Slope (ANS) crude
ii) Alberta Sweet Mixed Blend (ASMB) crude
iii) Arabian Heavy crude
iv) Arabian Light crude
v) Bonny Light crude
vi) Iranian Heavy crude
vii) Mayan crude
viii) automotive diesel

Two of these oils, Arabian Light and Mayan, were artificially weathered to two degrees of evaporation by bubbling air through them. The end points of the artificial evaporation were selected to approximate oil topped to 150°C and 250°C, after Durell *et al.* 1994. The physical properties of these oils are given in Tables 3.1 and 3.2.

3.2 Burn Experiments

The burns were conducted in a water-filled circular steel pan measuring 1.2 m in diameter and 32 cm in height (Figure 3.1). Measured amounts of the test oils were contained in the center of the pan in a 40 cm diameter, 20 cm high metal ring supported by three legs. The initial oil height was adjusted, by altering the water level, to be 1 cm below the lip of the ring. Three slick thicknesses were burned for each fresh oil: 5 cm, 10 cm and 15 cm. These were much greater than what has been used in other tests in order to simulate the slick thickness in fire-resistant booms under tow. Only 5 cm thicknesses of the artificially evaporated oils were burned. The burn tests were conducted at room temperature on 35 ppt salt water. A perforated ring of copper tubing connected to a constant-head supply tank was used to gently flush the bottom of the contained slick with cool salt water. This was done in order to better simulate slick conditions in a towed boom at sea. The purpose was to reduce or eliminate the vigorous burn phase (Evans *et al.* 1988 and 1992) that is often observed during smaller scale and static tests, but is not observed during larger scale tests at sea (Fingas *et al.* 1995). A fume hood suspended 1.5 m above the test ring, and connected to a fan (200 m^3/min) via 60 cm diameter flexible aluminum ducting, was used to exhaust the smoke generated by the burns.

Table 3.1 Physical Properties of Test Oils

Oil Type	Interfacial Tension (Dynes/cm)		Density (g/cm³)		Pour Pt. (°C)	Flash Pt. (°C)	Water Content (% wt/wt)
	oil/water	oil/air	@15°C	@40° C			
ANS	17.6	32.7	0.880	0.873	<-9	<7	0.080
Arab Hvy.	28.6	32.5	0.886	0.875	<-9	45	0.103
Arab Lt.	17	31.6	0.870	0.860	<-12	<7	0.430
20% Arab Lt.	16.6	32.5	0.908	0.899	-3	<9	0.093
31% Arab Lt.	14.8	35.8	0.926	0.912	3	9	0.104
ASMB	11.4	32.2	0.851	0.844	<-9	<10	0.336
Bonny Lt.	15	32.1	0.852	0.842	3	<6	0.080
Diesel	12.7	30.1	0.823	0.819	<-9	44	0.114
Iranian Hvy.	20.8	31.3	0.871	0.862	<-9	<8	0.169
Mayan	23.1	34.8	0.930	0.925	<-9	<6	0.301
12% Mayan	16.6	33.9	0.952	0.942	-6	<6	0.088
22% Mayan	N/M		0.975	0.958	9	30	0.144

Temperatures were measured at eleven locations in both the slick layer and the water below the slick. Flame temperatures were also recorded. The thermocouples (Type K) were connected to an A/D board, through a multiplexer to a computer. An adjustable rack was used so that eight of the thermocouples could be moved vertically and positioned at the same initial depth intervals below the oil surface for the different slick thicknesses. All burns were videotaped for archival purposes. After each burn the residue was collected and weighed, to permit the burn efficiency to be calculated, and samples taken for analyses.

For each test the following procedures were followed:

1) the mass and volume of oil to be burned was measured and recorded;

2) the oil was poured gently onto the water inside the burn ring;

3) the thermocouples were positioned to record temperatures of the slick, water and flame;

Table 3.2 Rheology of Test Oils

Oil Sample	Viscosity (mPas) @15°C	Shear Rate (s^{-1})	Viscosity (mPas) @40°C	Shear Rate (s^{-1})
ANS	21.2	3.7	10.5	7.3
	21.5	7.3	10.6	14.7
	22.0	14.7	11.6	36.7
Arab. Hvy	56.0	1.8	25.0	3.7
	56.0	3.7	23.0	7.3
	54.8	7.3	24.9	14.7
Arab. Lt.	19.0	3.7	9.5	7.3
	17.5	7.3	8.8	14.7
	18.0	14.7	8.8	36.7
			9.2	73.4
20% Arab. Lt.	90.0	1.3	25.0	2.6
	87.5	2.6	24.0	6.6
	89.0	6.6	25.0	13.2
	90.0	13.2		
31% Arab. Lt.	324.0	0.3	60.0	1.3
	330.0	0.7	60.0	2.6
	340.0	1.3	56.0	6.6
	347.5	2.6	55.5	13.2
ASMB	10.2	7.3	5.4	14.7
	10.5	14.7	5.0	36.7
	9.9	36.7	5.1	73.4
	9.8	73.4		
Bonny Lt.	21.5	3.7	3.5	14.7
	19.0	7.3	3.4	36.7
	16.5	14.7	3.6	73.4
	13.9	36.7		
Diesel	2.8	14.7	2.2	36.7
	2.5	36.7	2.1	73.4
	2.5	73.4		
Iranian Hvy.	18.2	3.7	11.0	7.3
	17.5	7.3	11.8	14.7
	17.3	14.7	12.3	36.7
	237.5	2.6	44.9	13.2
12% Mayan	2500.0	2.5	270.0	0.7
	2300.0	6.3	269.0	1.3
	2250.0	12.5	275.0	2.6
	1820.0	0.066		
	1560.0	0.132		
	1688.0	0.3		
	1768.0	0.7		
22% Mayan	32000.0	0.3	1700.0	0.1
	34000.0	0.6	1750.0	0.1
	35000.0	1.3	1700.0	0.3
	35750.0	2.5	1870.0	0.7

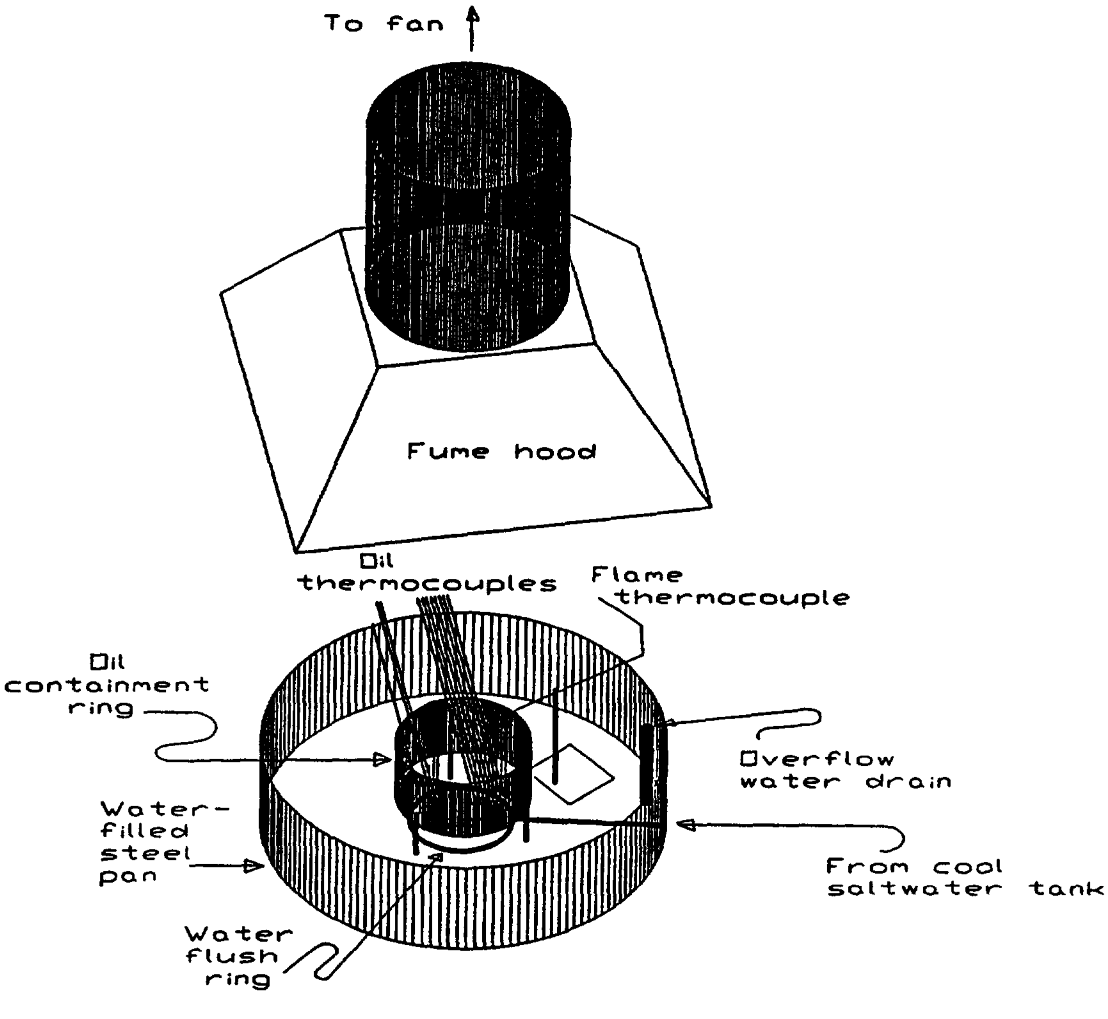

Figure 3.1 *Burn ring schematic*

4) the air and water temperatures were measured with a digital thermometer and recorded;

5) the video camera was started and the run number recorded on the tape;

6) the computer logging the thermocouple outputs was started;

7) the fume hood fan was started;

8) the slick was ignited with a propane torch;

9) the following times were recorded in a lab book, i) preheating time (the time for the flames to begin to spread away from the igniter), ii) the ignition time (the elapsed time for the flames to spread to cover the entire surface of the slick), iii) intense burn time (the elapsed time until the beginning of the vigorous burn phase), and iv) the extinction time (the elapsed time until the last flame goes out);

10) any unusual phenomenon, such as foaming observed during the burn, were noted;

11) at the end of the burn, the residue, once cooled, was collected and weighed;

12) a 200 mL aliquot of the residue was sealed in a labelled steel canister for subsequent shipment for the chemical analyses – the can was marked with the oil type, run number and date;

13) a 100 mL aliquot of the residue was sealed in a labelled glass jar for later physical property analyses;

14) any remaining residue was sealed in another labelled container of suitable size and stored in a refrigerator for possible later analysis; and,

15) the water in the burn ring was flushed until it had returned to ambient temperature in preparation for the next run.

3.3 Physical Property Analyses

<u>Fresh oil</u> samples were subjected to the following determinations:

- density at 15°C and 40°C using an Anton Parr Model DMA 35 digital densitometer and following ASTM D4052 procedures;

- dynamic viscosity at 15°C and 40°C at three shear rates using a Brookfield Model LV viscometer and following ASTM D2983 procedures;

- oil/seawater and oil/air interfacial tensions at room temperature using a Central Scientific Company DuNuoy Ring Apparatus following ASTM D971 procedures;

- pour point using the Kohler Pour Point Chamber and following ASTM D97 procedures;

- flash point using the Cleveland Open Cup apparatus following ASTM D93 procedures; and

- water content using an Orion Model AF8 Karl Fischer titrator following procedures developed by Environment Canada.

Burn residue samples were divided into two groups: those that were fluid at 45°C and those that were not. Residue samples that were fluid were analyzed to determine: density at 15°C and 40°C; viscosity at 15°C and 40°C, pour point and water content using the procedures described above for the fresh oil samples.

For those residue samples that were not fluid at 45°C, only their density was measured at 15°C and 40°C. This was accomplished by immersing a sample of the residue in a series of aqueous solutions. Twenty six solution baths were prepared to cover the density range 0.900 to 1.150 g/cm^3 in increments of 0.01 g/cm^3. The baths with densities less than water were made using methanol/water solutions; the baths with densities greater than water were prepared using sodium chloride/water solutions. Each residue sample was first placed in a pure water bath; depending on whether the sample sank or floated it was placed in solutions of progressively higher or lower density until one was found in which it floated or sank, respectively. At this point the density of the previous bath and the one in which the sample floated or sank was confirmed using the digital densitometer. The density of the residue sample was then assigned the value of the average of the density of the solution in the two baths. For the determination at 40°C both the residue sample and the aqueous solutions were maintained in a constant temperature bath.

3.4 Chemical Analyses

Both crude oil and burn residue were chemically characterized using a single common method. The basic chemical characterization method provided a measurement of each of total saturates, total aromatics, total resins, and total asphaltenes in each sample of either fresh oil or burn residue. The method involved four steps:

Step 1 Fractionating the sample into the boiling ranges: IBP to 204°C; 204°C to 538°C; and greater than 538°C using an ASTM D-1160 distillation.

Step 2 Analyzing the IBP to 204°C fraction by the Fluorescence Indicator Absorption Method (FIA – ASTM D-1319) to provide measurements of total aromatics, olefins, and saturates in the fraction.

Step 3 Analyzing the 204° to 538°C fraction using Bauxite Silica Gel Method (BSG – ASTM D-2549) to provide measurement of total saturates, aromatics and polars in the fraction.

Step 4 Analyzing the 538+°C fraction using a solvent/gravimetric method to provide measurements of total saturates, aromatics, resins and asphaltenes in the fraction.

The weights of each of the total saturates, total aromatics, total resins and total asphaltenes in the three fractions were summed to yield total weights of saturates, aromatics, resins, and asphaltenes for the residue samples.

All of the burn residues, with the exception of the diesel samples and the Bonny Light (15 cm burn residue), were heated to 163°C for two hours and then filtered through a 10 mesh screen to remove the solids. The solids in each sample were weighed and reported as a percent of the total sample. The ASTM D-1160 distillation and characterization of each fraction was then performed on the solids-free samples.

The diesel burn residues contained a low percentage of the IBP-204°C fraction which presented difficulties in obtaining a cut of this fraction by the ASTM D-1160 distillation. Several attempts were made to obtain this fraction, however the samples exhibited a high degree of foaming in the boiling flask, making it impossible to obtain this desired cut. Therefore, the burn residues were analyzed by simulated distillation (ASTM D-2887) to quantify the IBP-204°C fraction. Since the IBP-204°C fraction could not be practically obtained for these samples, the saturate/aromatic content by BSG - ASTM D-2549 was run on the burn residues as received.

4.0 Results and Discussion

4.1 Physical Property Data

Table 4.1 lists the oil and residue masses for each burn, as well as the overall duration of each burn (from ignition to extinction). All data and temperature readings for each burn are given in Appendix A. The 5 cm crude burns generally lasted 50 minutes; the 10 cm crude burns averaged 95 minutes; and, the 15 cm burns lasted 120 to 150 minutes. The exception was the 15 cm burn of Bonny Light which boiled over the lip of the ring 25 minutes after ignition. Among the crude oils, the ASMB consistently had the shortest burns. The diesel burned faster than the crudes, which is to be expected at this scale of burn (Buist *et al.* 1994).

Table 4.2 lists the burn efficiencies calculated for the test burns. Overall, burn efficiency (percent removal by weight) for the fresh crude oils ranged from 71 to 97%. The highest efficiency was consistently achieved with the diesel burns, with efficiencies of 98 to 99%, resulting in an amount of residue equivalent to less than 1 mm for all three initial thicknesses. All other burns resulted in amounts of residue equivalent to thicknesses greater than 2 mm. These results are consistent with the results of earlier studies (Buist *et al.* 1994). The least efficient burns involved Mayan crude, the oil with the highest density; the second least efficient burns involved Arab Heavy crude, the oil with the second highest density, etc. Weathering of the oil appeared to decrease burn efficiency slightly, an effect that has been noted before (Bech *et al.* 1992). This trend in the data in Table 4.2 is far from certain.

The burn with a 15 cm slick of Bonny Light crude was unique in that the oil boiled out of the burn ring about 25 minutes after ignition. The temperatures in the slick (Appendix A) indicate that the upper 5 cm of the slick was at a uniform temperature of 175°C after about 10 minutes, implying that abnormal convective heat transfer was occurring. The viscosity data in Table 3.2 indicate that the Bonny Light has an unusually steep decline in viscosity with increasing temperature which may explain the anomalous onset of convection. It is not clear why the Bonny Light behaved differently from the other crudes.

Table 4.3 lists the densities of the burn residues. Table 4.4 gives the densities and water contents of the residues from the burns that produced a liquid residue. Table 4.5 contains the viscosity data for the diesel burn residues. The burn residues of fresh crude oils ranged from 0.955 to 1.145 g/cm^3. It is worthy of note that none of the test burns experienced residue sinking until the burn had extinguished and the residue had cooled. In other words, at the slick temperatures during combustion (200 to 300°C), the density of the residue was less than that of the underlying water. As the residue cooled its density increased and eventually exceeded that of the water. The viscosity of the diesel residue was greater than that of the diesel fuel (see Table 3.2), but it was still a liquid. It should also be noted that, for all but the diesel tests and the failed 15 cm Bonny Light test, as the residue cooled it solidified. The residue from the heavier test oils (Iranian Heavy, Arab Heavy and Mayan) formed a brittle solid; the others (ANS, Arab Light, ASMB and Bonny Light) formed a semi-solid not unlike cold roofing tar. None of these residues softened appreciably at 45°C.

Table 4.1 Test Burn Data

	5 cm Burn			10 cm Burn			15 cm Burn		
Oil Type	Oil Mass (kg)		Burn Time (min.)	Oil Mass (kg)		Burn Time (min.)	Oil Mass (kg)		Burn Time (min.)
	Initial	Residue		Initial	Residue		Initial	Residue	
ANS	5.7200	0.8653	57.03	9.6800	0.9590	98.53	16.6798	1.5112	135.77
Arab. Hvy.	3.6492 ·	0.9066	49.13	10.9657	1.9454	92.00	16.9370	3.0000	153.85
Arab. Lt.	5.4436	0.3515	50.67	11.0041	0.2099	102.52	15.9465	1.9795	148.15
20% Arab. Lt.	5.9883	0.9564	66.10						
31% Arab. Lt.	6.1176	0.4780	62.12						
ASMB	5.7553	0.6638	37.67	11.2469	0.3016	83.50	16.3090	0.5847	118.38
Bonny Lt.	5.5380	0.5339	42.05	11.0760	0.5229	93.57	16.6140	BlowUp	
Diesel	5.3495	0.0748	25.65	10.6990	0.0715	49.33	16.0485	0.0548	65.78
Iranian Hvy.	5.5079	0.3428	43.33						
Mayan	6.0450	1.5076	49.97	11.5523	2.9736	94.23	17.4074	5.0367	144.00
12% Mayan	6.3963	1.7764	52.48						
22% Mayan	6.2037	1.8420	54.72						

Table 4.2 Test Burn Oil Removal Efficiencies

Oil Type	Burn Efficiency (Mass %)		
	5 cm Burn	**10 cm Burn**	**15 cm Burn**
ANS	84.9	91.6	90.9
Arab. Hvy.	75.2	82.3	90.9
Arab. Lt.	93.5	98.1	87.6
20% Arab. Lt.	84.0		
31% Arab. Lt.	92.2		
ASMB	88.5	97.3	96.4
Bonny Lt.	90.4	95.3	*
Diesel	98.6	99.3	99.7
Iranian Hvy.	93.8		
Mayan	75.1	74.3	71.1
12% Mayan	72.2		
22% Mayan	70.3		

* This sample boiled over and the burn was not complete

Table 4.3 Burn Residue Densities

Oil Type	Density @ 15°C (g/cm^3)			Density @ 40°C (g/cm^3)		
	5 cm	10 cm	15 cm	5 cm	10 cm	15 cm
ANS	1.025	1.075	1.045	1.020	1.068	1.040
Arab. Hvy.	1.125	1.125	1.065	1.107	1.084	1.020
Arab. Lt.	1.035	1.065	1.065	1.020	1.030	1.069
20% Arab. Lt.	1.065			1.050		
31% Arab. Lt.	1.075			1.069		
ASMB	0.985	1.015	1.055	0.971	1.011	1.040
Bonny Lt.	0.955	0.975	0.873	0.971	0.981	0.865
Diesel	0.879	0.885	0.883	0.870	0.877	0.875
Iranian Hvy.	1.055			1.030		
Mayan	1.125	1.145	1.095	1.084	1.084	1.059
12% Mayan	1.135			1.107		
22% Mayan	1.135			1.116		

* This sample boiled over and the burn was not complete

Table 4.4 Liquid Burn Residue Properties

Residue	Water Content (% wt/wt)	Pour Point (°C)	Density	
			@ 15°C (g/cm^3)	@ 40°C (g/cm^3)
Diesel 5cm	2.859	<-12	0.885	0.870
Diesel 10cm	4.160	<-9	0.879	0.877
Diesel 15cm	7.100	<-9	0.883	0.875
Bonny Lt. 15cm	3.382	N/M	0.873	0.865

Table 4.5 Burn Residue Viscosity Data

Burn Residue	T = 15°C Viscosity (mPas)	Shear Rate (s^{-1})	T = 40°C Viscosity (mPas)	Shear Rate (s^{-1})
Diesel 5cm	11.5	7.344	9.5	14.688
	12.6	14.688	9.4	36.72
	13.44	36.72	9.25	73.44
Diesel 10cm	28	3.672	20	3.672
	27	7.344	18.5	7.344
	25	14.688	17.25	14.688
			15.35	36.72
Diesel 15cm	21	3.672	14.1	7.344
	21.5	7.344	14	14.688
	21	14.688	12.2	36.72
	19	36.72		

4.2 Residue Density Increase

Figure 4.1 shows the increase in residue density at 15°C with increasing initial oil thickness for the eight fresh oils tested. The horizontal lines show the density of fresh water (1.000 g/cm^3) and normal sea water (1.025 g/cm^3). It is clear that efficient burning of thick slicks does significantly increase the density of the residue, and may do so to a point where the residue can sink. It is also apparent that heavier crude oils produce residues that are more susceptible to sinking. The density of the residue from the diesel burns does not appear to increase as much as for crude oils and, after an initial increase, appears not to be a strong function of slick thickness.

Buist *et al.* (1995) reported that the residue from a contained burn of 17.5 cm of fresh ANS crude sank in both sea water and fresh water as it cooled. The data in this study are consistent with this observation (see Figure 4.1) in that the density of the residue from the 10 and 15 cm burns of ANS crude exceeded 1.025 g/cm^3 at 15°C. Fingas *et al.* (1995) report that the residue from the NOBE offshore burn of ASMB crude had a density of 0.936 g/cm^3 and a viscosity of 100,000 mPas. This apparent contradiction of the results presented here for ASMB crude is possibly due to the fact that the NOBE burn involved a continuous feed of fresh oil into the burn pocket of a towed boom, as opposed to a burn of a thick contained slick as in the present study.

The properties of the residues from the Iranian Heavy and Arabian Heavy test burns appear to be consistent with the properties of burn residue from actual spills of these oils. Some of the residue from the accidental burning of uncontained thick slicks of Iranian Heavy crude oil beside the stricken tanker M/T *Haven* is reported to have sunk to the seabed (Moller 1992, Turbini *et al.* 1993). The residue from the 5 cm burn of Iranian Heavy crude in the present study had a density that exceeded that of salt water. After a spill of some 2000 tonnes of Arabian Heavy crude from the M/T *Honam Jade* a cleanup contractor ignited the main slick which burned for two hours; after the burn extinguished the residue sank (Moller 1992). The residue from all three burns of Arab Heavy crude in the present study had densities greater than sea water at both 15° and 40°C.

Figure 4.2 illustrates the effect of weathering of a crude oil on the density of the burn residue. The density of the residue from 5 cm slicks of Arab Light crude increases with increasing degree of evaporation. Perusal of the data in Table 4.3 indicates that the same trend appears to have occurred for densities measured at 40°C.

4.3 Preliminary Residue Density Correlation

One of the goals of this study was to attempt to correlate burn residue properties with oil- and/or burn-parameters. A preliminary model is presented here.

If the fuel vaporization process involved with in-situ burning is like an imperfect EFV, then it should be possible to correlate changes in residue density with initial slick properties and a measure of the degree of concentration of heavy ends that occurs during a given burn. It seems logical that the degree of concentration, for a given oil, should relate to the amount of oil burned and the efficiency of the burn. One expression that incorporates both of these factors is the product of the burn efficiency and the initial thickness or:

$$\rho/\rho_o = f\,(F_{BV}X_o) \qquad (1)$$

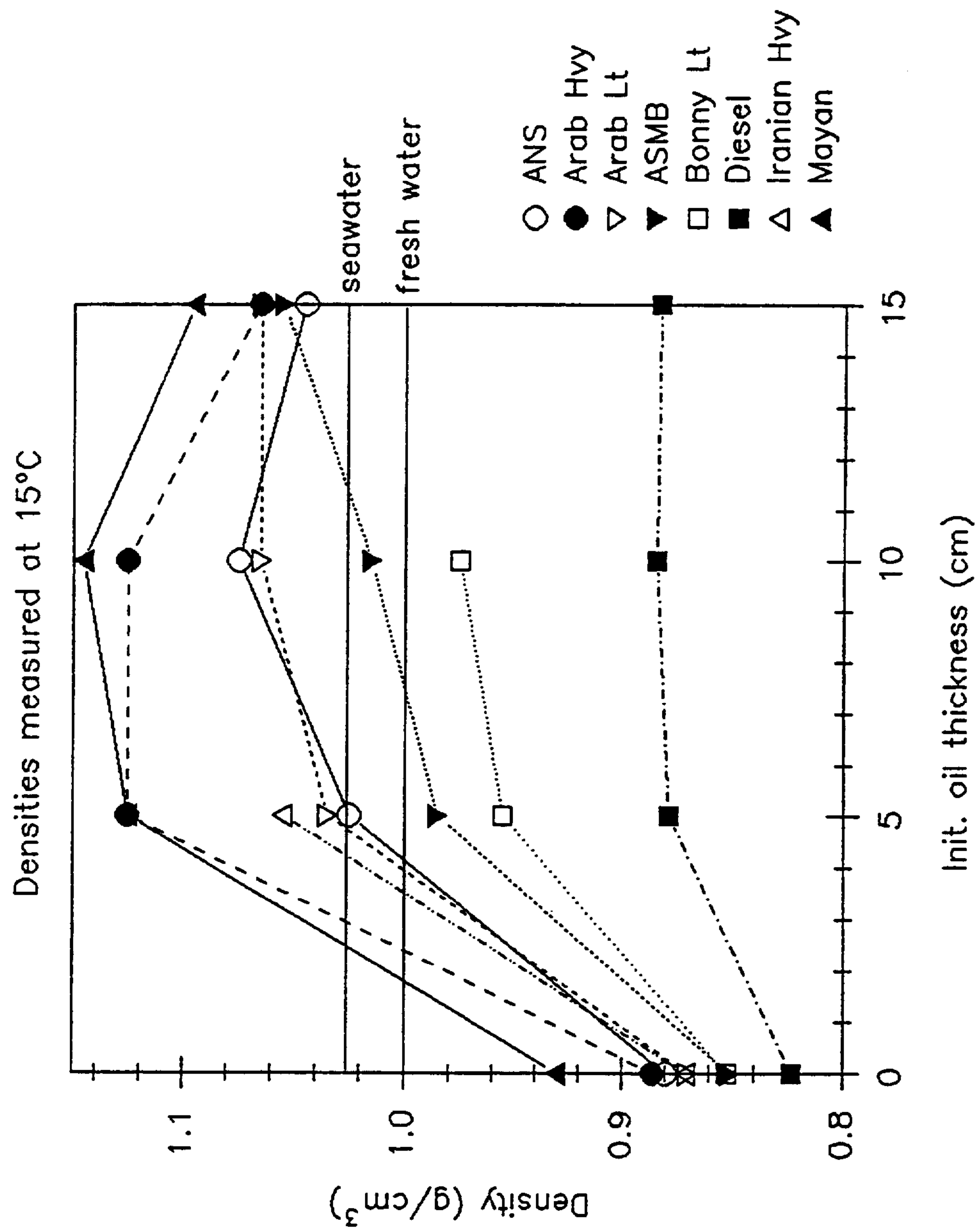

Figure 4.1 Residue density

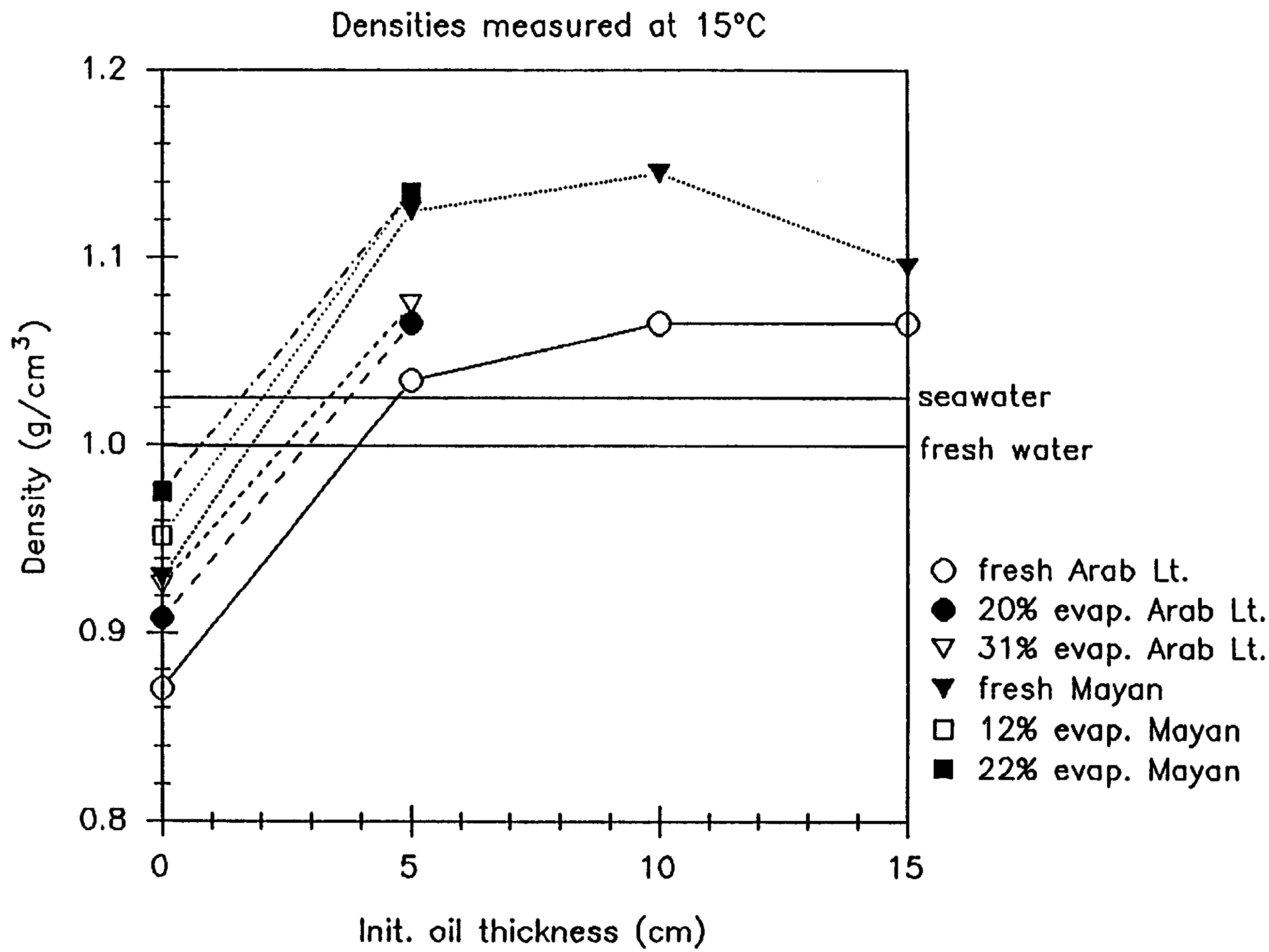

Figure 4.2 Effect of evaporation on residue density

where ρ, ρ_o ≡ the residue and initial oil density respectively [g/cm^3]
F_{BV} ≡ volumetric fraction of oil burned
X_o ≡ initial oil thickness [cm]

The term $F_{BV}X_o$ is equivalent to the thickness of oil burned.

The volumetric fraction of oil burned can be calculated from the mass fraction burned (F_{BM}) by:

$$(1 - F_{BV}) = (1 - F_{BM})\rho_o/\rho \tag{2}$$

Figure 4.3 shows a plot of the ratio of residue density to fresh oil density as a function of $F_{BV}X_o$. This graph uses the densities at 40°C. It appears that there is a common trend of increasing density ratio with increasing amount of oil burned; however, the data scatter is fairly high. This could be due to inaccuracies in the density measurements, oil-related factors and/or burn-process-related factors. The possible contribution of the vigorous burn phase to the data scatter is discussed later.

One interesting feature of Figure 4.3 is that the data for the crude oils are generally grouped around a common trend, with the exception of the residue from the 5 cm thick burn of Arab Heavy crude, while the data for the diesel fuel are distinctly different. This could be due to the fact that diesel, as a refined fuel, has few heavy ends to concentrate, and thus the residue is not significantly different from the original fuel. This aspect is discussed later in Section 4.4.

The data appears to fit an equation of the form:

$$\rho/\rho_o = 1+C_1(1 - \exp(-C_2F_{BV}X_o)) \tag{3}$$

where C_1 ≡ a constant, which appears to have a value in the range of 0.2 for crude oils and 0.07 for diesel
C_2 ≡ another constant [cm^{-1}] which appears to have a value in the range of 0.33 cm^{-1}

This equation has the properties that:

- as either F_{BV} or X_o approaches 0 the density of the residue approaches the density of the initial oil;

- as the power of the exponential increases the density ratio increases, rapidly at first but more slowly as the power increases. This seems reasonable for an imperfect EFV process, each increment of heavy ends added to the remaining slick would result in a progressively smaller increase in the density of the remaining slick;

- the density ratio tends to a maximum value on the order of 1.20 for crudes and 1.07 for diesel (this value may be oil-type controlled).

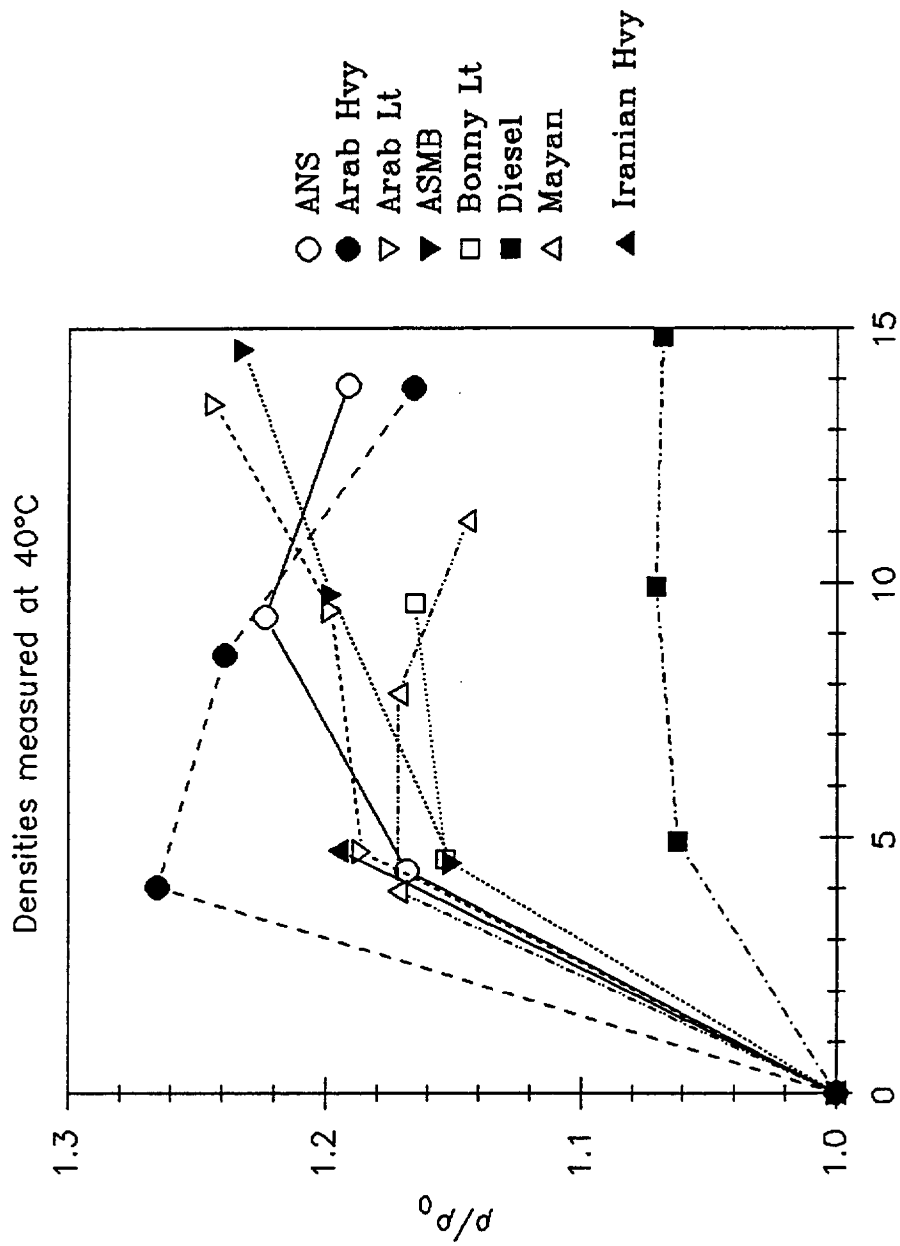

***Figure 4.3** Correlation of density ratio*

The fit of equation 3 to the data is illustrated in Figure 4.4. Further tests will be required to determine any scaling factors (i.e., burn diameter).

Several of the oils appear to produce residues with densities and density ratios that reach a maximum, then decline. Specifically these are Arabian Heavy, ANS and Mayan. It is believed that this may be due to the onset of a long vigorous burn phase during the test with these oils (Appendix A). The 15 cm thick burn of Arab Heavy experienced a 10 minute vigorous burn phase, as opposed to 3 to 4 minutes for the 5 and 10 cm burns. Likewise the 15 cm ANS burn involved a 5 minute vigorous burn phase in comparison with 1 to 2 minutes for the 5 and 10 cm burns. All three thicknesses of Mayan crude burned involved vigorous burn phases with durations of 6 to 7 minutes. The remainder of the oils had vigorous burn phases that did not increase dramatically with increasing thicknesses and were in the 1 to 3 minute range. The combustion process during the vigorous burn phase is fundamentally different than during steady burning; the vigorous burn phase involves droplets of liquid oil being propelled into the combustion zone above the slick where they vaporize and burn completely. This atomization process would not involve concentration of heavy ends in the remaining slick, but would be a true EFV. This would mean that the early onset of a vigorous burn phase would result in a burn residue with a lower density than would otherwise be expected. It should be noted that the vigorous burn phase is likely an artifact of the test apparatus; this phenomena may not occur at sea.

Guenette *et al*. (1994) presented the following equations for the increase in density for burn residues of Statfjord and ANS crude.

$$\rho = 0.908 + 0.03\ F_{BV}\ [g/cm^3] \text{ for Statfjord crude} \tag{4}$$

$$\rho = 0.942 + 0.03\ F_{BV}\ [g/cm^3] \text{ for ANS crude} \tag{5}$$

Although based on a statistical analysis of residue densities from 0.5, 1 and, 2 cm thick burns, these correlations do not appear to adequately represent situations beyond these bounds. For example, the density at 15°C of the ANS crude used in their experiments was 0.878 g/cm^3 whereas equation 5, with F_{BV}=0 would predict a density of 0.942 g/cm^3. It is also clear that, for thick slicks of ANS crude, it is possible for the burn residue density to exceed 1.025 g/cm^3, whereas the maximum predicted density from equation 5 is 0.972 g/cm^3. It is interesting to note that this maximum predicted residue density, divided by their reported fresh oil density gives a ratio of 1.1, which is almost identical to the value predicted by Equation 3 for a 95% efficiency burn of a 2 cm thick slick of crude oil.

Figure 4.5 shows the density ratios measured at 15°C as a function of $F_{BV}X_o$. The anomalous behavior of the Bonny Light crude is again apparent. It is not clear why this crude behaves differently from the others.

For the other oils plotted on Figure 4.5, comparison with Figure 4.4 shows that the use of a density ratio adequately deals with measurement temperature effects; that is to say that the trend in the data do not appear to be a strong function of the temperature at which the two densities are measured.

Figure 4.6 shows the effect of evaporation of the oil prior to burning on the density ratio. Considering the data scatter in Figure 4.5, no conclusions can be drawn; however, it appears that increased evaporation may cause a slight reduction in burn residue density ratio.

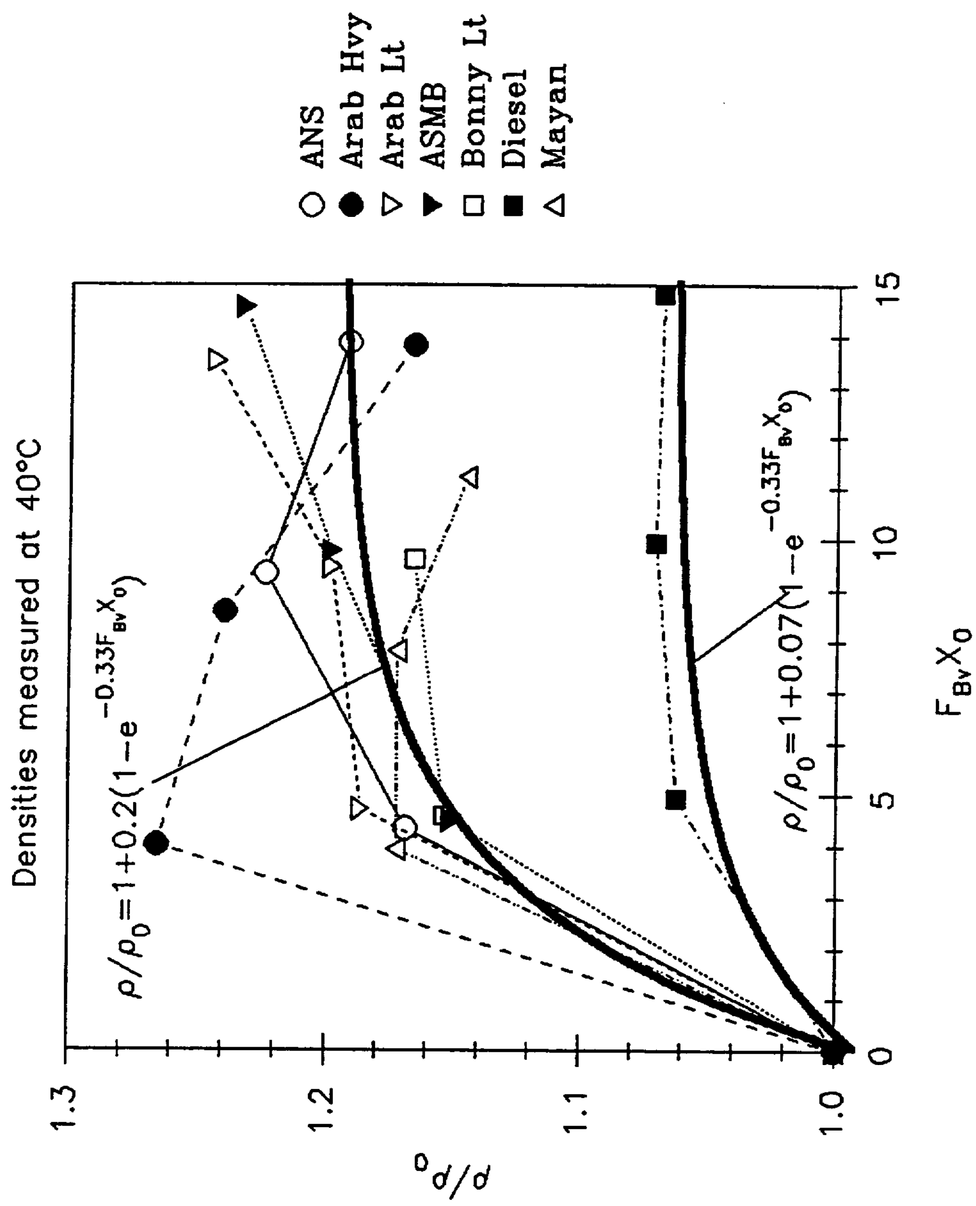

***Figure 4.4** Comparison of model with data*

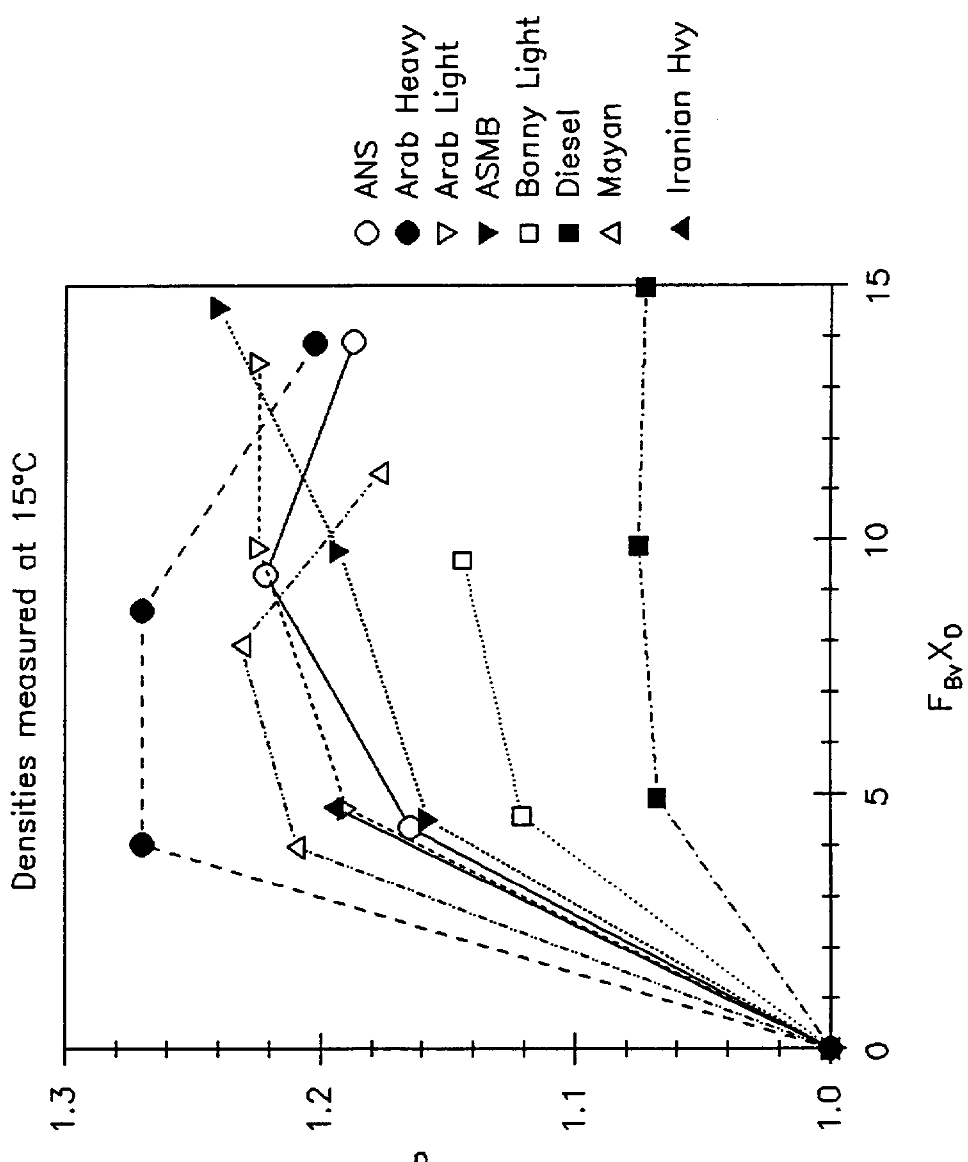

Figure 4.5 ***Density ratio at 15°C***

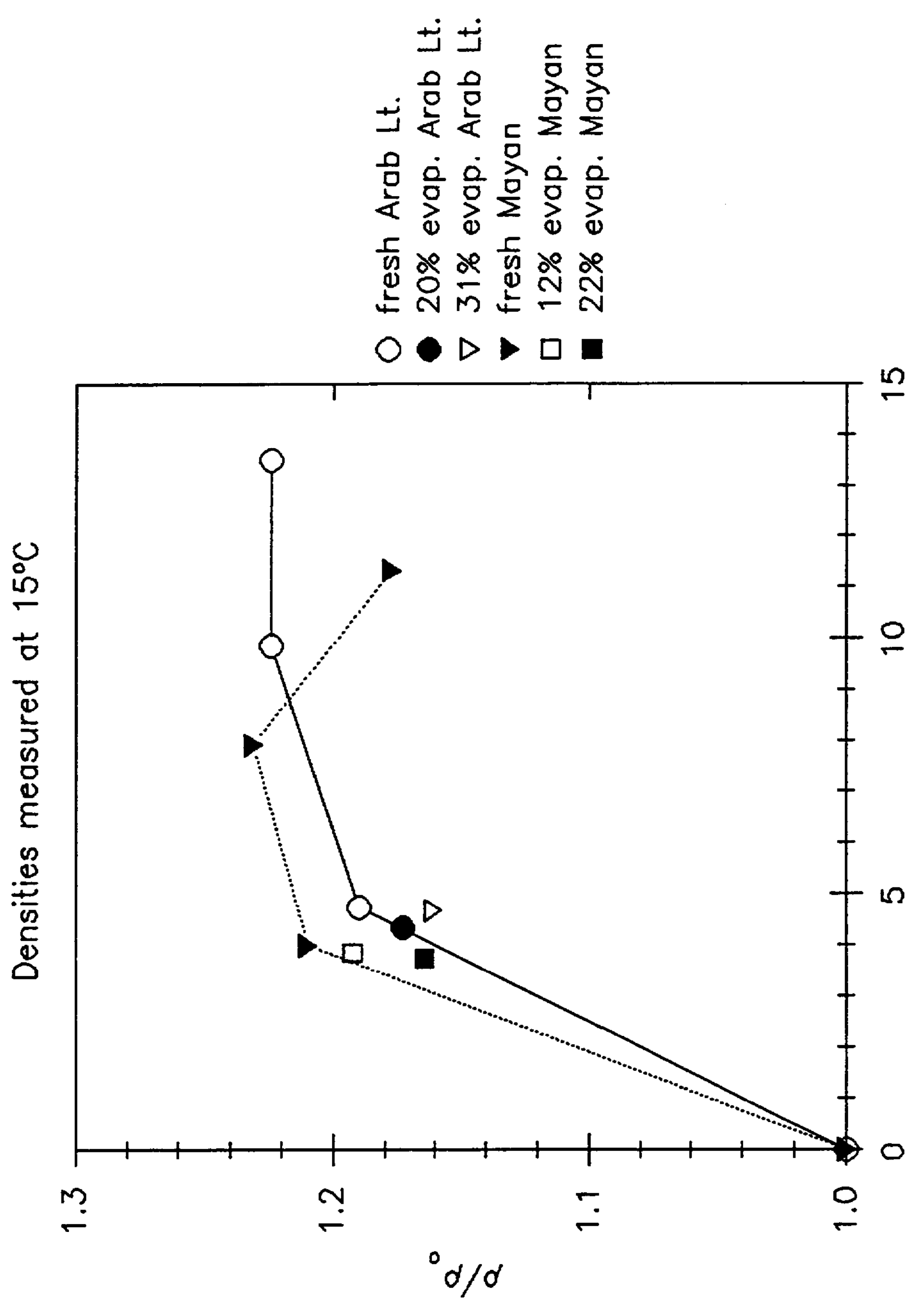

Figure 4.6 Effect of evaporation on density ratio

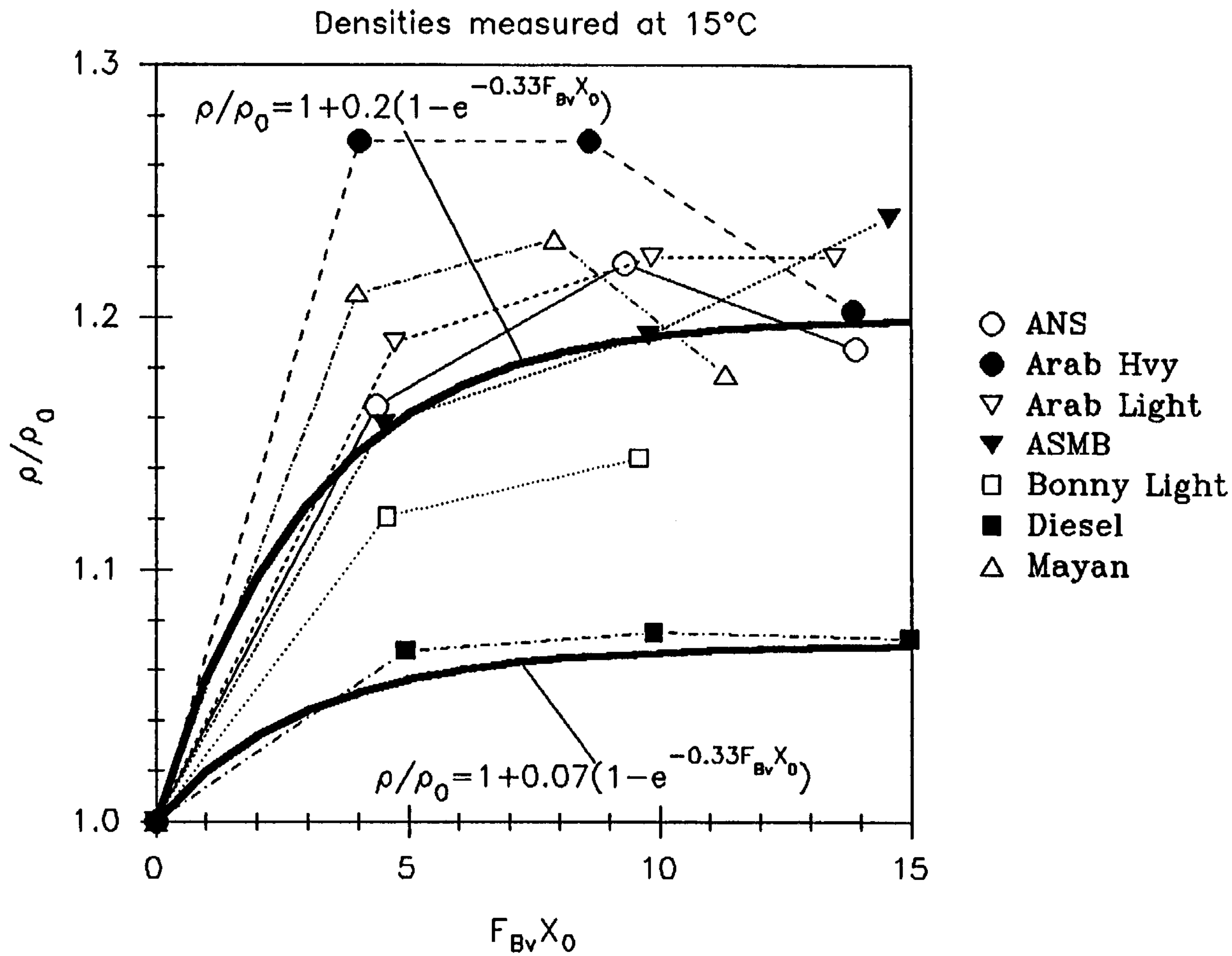

Figure 4.7 *Comparison of model with data*

Figure 4.7 compares the residue density ratios measured at 15°C with the model equation (3). Although the fit is far from perfect, the trends appear similar.

4.4 Chemical Analysis Data

Table 4.6 summarizes the results of the chemical analyses of the ANS crude and the three burn residues. The Core Laboratories report for all the oils is reproduced in Appendix B.

The residues from the ANS burns did contain solid materials (at 163°C). The amount ranged from 5 to 21%. The composition of these solid materials was not determined. They could be: very high molecular weight hydrocarbons precipitated out of the oil as a result of the combustion process; ash or soot from the combustion zone that falls back onto the liquid surface during the burn; or, salts from evaporated water incorporated into the residue during the vigorous burn phase.

The yield data for the ANS burn residues (performed on the filtrate from the solids removal step described above) indicates that:

- none of the ANS burn residues contained any of the lower boiling point compounds;

- all of the residues did contain some medium volatility compounds, indicating that imperfect EFV was occurring; and

- over 90% of the liquid (at 163°C) residue was composed of heavy ends (the maximum boiling points of the residues achieved at atmospheric pressure is shown in Table 4.6).

The distribution of the types of compounds in the various distilled fractions are also given in Table 4.6. The percentage of each fraction composed of saturates declines with increasing boiling point range.

In order to better understand the composition of the residue and changes to it that occur as a result of in-situ burning, Table 4.7 was prepared. The basis for Table 4.7 is 100 grams of fresh ANS crude burned. The first three rows in Table 4.7 show the weight of residue (total, solid and liquid) generated from the 100 g of fresh oil for each of the burn tests. The next three rows show the weight of liquid residue in each of the three boiling point ranges. The next three rows give the volumes (converted from weights using the fresh oil density) of saturates, olefins and aromatics in the IBP to 204°C boiling point range fraction (representing up to approximately C_{12}); only the fresh crude contains these compounds.

The next three rows gives the grams of saturates, aromatics and polar aromatics in the fraction that boils between 204°C and 538°C. In comparison with the fresh crude, the combustion process has greatly reduced the amount of material in every class of compounds in this boiling fraction.

The next four rows of data give the weights of the various types of compounds in the residual fraction with boiling points greater than 538°C. The amounts of the various types are not greatly less than was in 100 grams of the fresh crude, and in fact the mass of asphaltenes remaining in the residues is nearly the same as in the original crude. This lends further credence to the imperfect EFV theory – the heaviest compounds are concentrated in the residue and not burned.

Table 4.6 Chemical Composition Data for ANS Crude

	Alaska North Slope			
	Crude	**5 cm Burn**	**10 cm Burn**	**15 cm Burn**
Burn Efficiency (Wt %)		84.9	91.6	90.9
Percent Solid (Wt. %)		8.88	4.97	21.21
Yield by ASTM D-1160 (Wt. %)				
IBP - 204 °C	17.24	0.00	0.00	0.00
204 - 538 °C	57.74	9.60	6.31	8.76
538 °C Plus	25.02	90.40	93.69	91.24
Total	100.00	100.00	100.00	100.00
Initial Boiling Point (°C)	N/M	295	N/M	310
Max. Distillation Temp. Obtained (°C)	538	496	522	503
FIA - ASTM D-1319 (IBP - 204 °C)				
Saturates (LV %)	91.00			
Olefins (LV %)	0.00			
Aromatics (LV %)	9.00			
Total (LV %)	100.00			
BSG - ASTM D-2549 (204-538 °C)				
Saturates (Wt %)	58.26	42.54	39.35	38.69
Aromatics (Wt %)	38.85	53.39	56.48	56.72
Polar Aromatics (Wt %)	2.89	4.07	4.17	4.59
Total (Wt. %)	100.00	100.00	100.00	100.00
SARA (538 °C Plus)				
Saturates (Wt %)	14.60	8.38	7.05	7.36
Aromatics (Wt %)	53.10	38.83	36.54	37.87
Resins (Wt %)	16.77	12.69	12.18	10.90
Asphaltenes (Wt %)	15.53	40.10	44.23	43.87
Total (Wt %)	100.00	100.00	100.00	100.00

Table 4.7 Mass Balance Data for ANS Crude

Based on 100 g of crude oil burned	Alaska North Slope				
	Crude		5 cm Burn	10 cm Burn	15 cm Burn
Weight of residue (g)			15.1	8.4	9.1
Weight of solid residue (g)			1.34	0.41	1.93
Weight of liquid residue (g)			13.75	7.98	7.16
Weight of IBP-204 °C cut (g)	17.24		0.00	0.00	0.00
Weight of 204-538 °C cut (g)	57.74		1.32	0.50	0.62
Weight of 538 °C plus cut (g)	25.02		12.43	7.47	6.54
	@15°C	@40°C			
Amount of saturates in IBP-204 °C (mL)	17.82	17.97	0.00	0.00	0.00
Amount of olefins in IBP-204 °C (mL)	0.00	0.00	0.00	0.00	0.00
Amount of aromatics in IBP-204°C (mL)	1.76	1.77	0.00	0.00	0.00
Weight of saturates in 204-538 °C (g)	33.63		0.56	0.19	0.24
Weight of aromatics in 204-538 °C (g)	22.43		0.70	0.28	0.35
Weight of polar aromatics in 204-538 °C (g)	1.66		0.05	0.02	0.02
Weight of saturates in 538 °C plus (g)	3.65		1.04	0.52	0.48
Weight of aromatics in 538 °C plus (g)	13.28		4.82	2.73	2.47
Weight of resins in 538 °C plus (g)	4.19		1.57	0.91	0.71
Weight of asphaltenes in 538 °C plus (g)	3.88		4.98	3.30	2.86
Total saturates (g)			1.60	0.72	0.72
Total aromatics (g)			5.53	3.01	2.83
Total polar aromatics (g)			0.05	0.02	0.02
Total resins (g)			1.57	0.91	0.71
Total asphaltenes (g)			4.98	3.30	2.86
Composition of Liquid residue					
Saturates (Wt %)			11.65	9.08	10.10
Aromatics (Wt %)			40.22	37.79	39.52
Polar Aromatics (Wt %)			0.39	0.26	0.40
Resins (Wt %)			11.47	11.41	9.94
Asphaltenes (Wt %)			36.25	41.43	40.02

The next five rows give the weights of saturates, aromatics, polar aromatics, resins and asphaltenes in the liquid burn residue samples. These were arrived at by summing the various categories in the previous seven rows. These weights were then used to calculate the composition of the liquid residue shown in the last five rows of the table. The fact that the concentration of asphaltenes has increased from 3.9% in the crude to about 40% in the residue is indicative of an imperfect EFV process; the concentration of resins has similarly increased from 4% in the crude to about 10% in the residues. The fact that the burn residues are composed of approximately 50% asphaltenes and resins and between 5 and 20% solid material (at 163°C) accounts for their semi-solid rheology at ambient temperatures.

Table 4.8 shows the chemical analysis data for the ASMB fresh crude and residues. There appears to be a trend of increasing solids content in the residue with increasing slick thickness burned. As with the ANS, there are no volatiles (IBP-204°C or about C_{12}) in any of the residues. The data in Table 4.9 for the ASMB crude show that the asphaltenes appear to concentrate in the residue during the burn process and are not appreciably consumed. As with the ANS residue the high asphaltene, resin and solids (at 163°C) contents of the ASMB burn residues (particularly from the 10 and 15 cm burns) account for the semi-solid rheology of the samples at ambient temperatures.

Table 4.10 gives the results for the Arabian Heavy crude and burn residues. No trend in residue solids content is apparent. None of the residues contained any volatile fraction (IBP to 204°C). The mass balance data in Table 4.11 shows that, for the residues from the 5 and 10 cm burn, the asphaltenes were preserved in the residue. The anomalous result for the residue from the 15 cm burn may be explained by the fact that the end of this burn involved an exceptionally long vigorous burn phase. This type of burning involves atomization of the slick as opposed to vaporization and would be expected to produce a different residue than imperfect EFV. The density of the residue from this burn was also unexpectedly low. The near-solid rheology of the residues at room temperatures can be attributed to their high asphaltene, resin and solids concentrations.

Table 4.12 summarizes the results for the Bonny Light crude and residues. This oil differed from the other crudes in that it had a very low non-volatile content (greater than 538°C) and none of the residues contained any solids at 163°C.

The residues from the 5 and 10 cm burns contained no volatiles; however, the residue from the 15 cm burn that boiled prematurely did contain volatiles. This fact supports the imperfect EFV theory of in-situ burning – if a batch-type distillation process was occurring the low-boiling point fraction would be expected to be greatly diminished at the point in the burn when the boil over occurred (after 25 minutes or some 20% of the expected burn time).

Perusal of the mass composition data for the 5 and 10 cm Bonny Light burn residues in Table 4.13 shows that the asphaltenes were preserved. The semi-solid nature of these two residues can be attributed to their increased asphaltene and resin contents.

Table 4.14 presents the results of the chemical analyses of the Iranian Heavy crude and 5 cm burn residue. The residue contained: 4.2% solids at 163°C; no volatiles with boiling points less than 204°C (approximately C_{12}); and, 87% non-volatiles (boiling points greater than 538°C). Table 4.15 presents the composition data based on 100 g of Iranian Heavy crude burned. The amount of asphaltenes remaining in the residue is lower than in the fresh crude, by a factor of about 3. The concentration of asphaltenes and resins in the residue was 42%, explaining the near-solid rheology of the residue sample at ambient temperatures.

Table 4.8 Chemical Composition Data for ASMB Crude

	Alberta Sweet Mixed Blend			
	Crude	5 cm Burn	10 cm Burn	15 cm Burn
Burn Efficiency (%)		88.5	97.3	96.4
Percent Solid (Wt. %)		0.62	17.22	34.06
Yield by ASTM D-1160 (Wt. %)				
IBP - 204 °C	21.87	0.00	0.00	0.00
204 - 538 °C	63.65	25.66	7.60	4.03
538 °C Plus	14.48	74.34	92.40	95.97
Total	100.00	100.00	100.00	100.00
Initial Boiling Point (°C)	N/M	370	382	331
Max. Distillation Temp. Obtained (°C)	538	538	513	482
FIA - ASTM D-1319 (IBP - 204 °C)				
Saturates (LV %)	86.00			
Olefins (LV %)	0.80			
Aromatics (LV %)	13.20			
Total (LV %)	100.00			
BSG - ASTM D-2549 (204-538 °C)				
Saturates (Wt %)	66.88	51.55	46.75	48.98
Aromatics (Wt %)	30.58	44.44	48.46	47.36
Polar Aromatics (Wt %)	2.54	4.01	4.79	3.66
Total (Wt. %)	100.00	100.00	100.00	100.00
SARA (538 °C Plus)				
Saturates (Wt %)	26.89	22.01	11.25	9.51
Aromatics (Wt %)	47.21	49.69	38.50	35.73
Resins (Wt %)	14.75	14.15	10.50	8.82
Asphaltenes (Wt %)	11.15	14.15	39.75	45.94
Total (Wt %)	100.00	100.00	100.00	100.00

Table 4.9 Mass Balance Data for ASMB Crude

Based on 100 g of crude oil burned	Alberta Sweet Mixed Blend			
	Crude	**5.00 cm Burn**	**10.00 cm Burn**	**15.00 cm Burn**
Weight of residue (g)		11.50	2.70	3.60
Weight of solid residue (g)		0.07	0.46	1.23
Weight of liquid residue (g)		11.43	2.24	2.37
Weight of IBP-204 °C cut (g)	21.87	0.00	0.00	0.00
Weight of 204-538 °C cut (g)	63.65	2.93	0.17	0.10
Weight of 538 °C plus cut (g)	14.48	8.50	2.07	2.28
	@15°C @40°C			
Amount of saturates in IBP-204 °C (mL)	22.10 22.28	0.00	0.00	0.00
Amount of olefins in IBP-204 °C (mL)	0.21 0.20	0.00	0.00	0.00
Amount of aromatics in IBP-204°C (mL)	3.39 3.42	0.00	0.00	0.00
Weight of saturates in 204-538 °C (g)	42.57	1.51	0.08	0.05
Weight of aromatics in 204-538 °C (g)	19.46	1.30	0.08	0.05
Weight of polar aromatics in 204-538 °C (g)	1.62	0.12	0.01	0.00
Weight of saturates in 538 °C plus (g)	3.89	1.87	0.23	0.22
Weight of aromatics in 538 °C plus (g)	6.84	4.22	0.80	0.81
Weight of resins in 538 °C plus (g)	2.14	1.20	0.22	0.20
Weight of asphaltenes in 538 °C plus (g)	1.61	1.20	0.82	1.05
Total saturates (g)		3.38	0.31	0.26
Total olefins (g)		0.00	0.00	0.00
Total aromatics (g)		5.52	0.88	0.86
Total polar aromatics (g)		0.12	0.01	0.00
Total resins (g)		1.20	0.22	0.20
Total asphaltenes (g)		1.20	0.82	1.05
Composition of Liquid residue				
Saturates (Wt %)		29.59	13.95	11.10
Olefins (Wt %)		0.00	0.00	0.00
Aromatics (Wt %)		48.34	39.26	36.20
Polar Aromatics (Wt %)		1.03	0.36	0.15
Resins (Wt %)		10.52	9.70	8.46
Asphaltenes (Wt %)		10.52	36.73	44.09

Table 4.10 Chemical Composition Data for Arabian Heavy Crude

	Arabian Heavy			
	Crude	5 cm Burn	10 cm Burn	15 cm Burn
Burn Efficiency (%)		75.2	82.3	90.9
Percent Solid (Wt. %)		9.43	0.49	13.11
Yield by ASTM D-1160 (Wt. %)				
IBP - 204 °C	15.62	0.00	0.00	0.00
204 - 538 °C	49.88	9.26	8.21	8.70
538 °C Plus	34.50	90.74	91.79	91.30
Total	100.00	100.00	100.00	100.00
Initial Boiling Point (°C)	N/M	344	325	325
Max. Distillation Temp. Obtained (°C)	534	506	509	539
FIA - ASTM D-1319 (IBP - 204 °C)				
Saturates (LV %)	93.80			
Olefins (LV %)	0.00			
Aromatics (LV %)	6.20			
Total (LV %)	100.00			
BSG - ASTM D-2549 (204-538 °C)				
Saturates (Wt %)	56.22	36.40	35.92	36.03
Aromatics (Wt %)	42.06	60.50	60.82	59.37
Polar Aromatics (Wt %)	1.72	3.10	3.26	4.60
Total (Wt. %)	100.00	100.00	100.00	100.00
SARA (538 °C Plus)				
Saturates (Wt %)	10.98	6.19	6.35	8.41
Aromatics (Wt %)	52.61	39.85	40.32	42.06
Resins (Wt %)	11.27	8.17	12.06	10.28
Asphaltenes (Wt %)	25.14	45.79	41.27	39.25
Total (Wt %)	100.00	100.00	100.00	100.00

Table 4.11 Mass Balance Data for Arabian Heavy Crude

Based on 100 g of crude oil burned	Arabian Heavy			
	Crude	**5.00 cm Burn**	**10.00 cm Burn**	**15.00 cm Burn**
Weight of residue (g)		24.80	17.70	9.10
Weight of solid residue (g)		2.34	0.09	1.19
Weight of liquid residue (g)		22.46	17.61	7.91
Weight of IBP-204 °C cut (g)	15.62	0.00	0.00	0.00
Weight of 204-538 °C cut (g)	49.88	2.08	1.45	0.69
Weight of 538 °C plus cut (g)	34.50	20.38	16.17	7.22
	@15°C @40°C			
Amount of saturates in IBP-204 °C (mL)	16.54 16.74	0.00	0.00	0.00
Amount of olefins in IBP-204 °C (mL)	0.00 0.00	0.00	0.00	0.00
Amount of aromatics in IBP-204°C (mL)	1.09 1.10	0.00	0.00	0.00
Weight of saturates in 204-538 °C (g)	28.04	0.76	0.52	0.25
Weight of aromatics in 204-538 °C (g)	20.98	1.26	0.88	0.41
Weight of polar aromatics in 204-538 °C (g)	0.86	0.06	0.05	0.03
Weight of saturates in 538 °C plus (g)	3.79	1.26	1.03	0.61
Weight of aromatics in 538 °C plus (g)	18.15	8.12	6.52	3.04
Weight of resins in 538 °C plus (g)	3.89	1.67	1.95	0.74
Weight of asphaltenes in 538 °C plus (g)	8.67	9.33	6.67	2.83
Total saturates (g)		2.02	1.55	0.85
Total aromatics (g)		9.38	7.40	3.44
Total polar aromatics (g)		0.06	0.05	0.03
Total resins (g)		1.67	1.95	0.74
Total asphaltenes (g)		9.33	6.67	2.83
Composition of Liquid residue				
Saturates (Wt %)		8.99	8.78	10.81
Aromatics (Wt %)		41.76	42.00	43.57
Polar Aromatics (Wt %)		0.29	0.27	0.40
Resins (Wt %)		7.41	11.07	9.39
Asphaltenes (Wt %)		41.55	37.88	35.84

Table 4.12 Chemical Composition Data for Bonny Light Crude

	Bonny Light			
	Crude	**5 cm Burn**	**10 cm Burn**	**15 cm Burn**
Burn Efficiency (%)		90.4	95.3	*
Percent Solid (Wt. %)		0.00	0.00	0.00
Yield by ASTM D-1160 (Wt. %)				
IBP - 204 °C	20.61	0.00	0.00	28.60
204 - 538 °C	71.81	41.46	14.70	59.81
538 °C Plus	7.58	58.54	85.30	11.59
Total	100.00	100.00	100.00	100.00
Initial Boiling Point (°C)	N/M	288	307	N/M
Max. Distillation Temp. Obtained (°C)	538	538	531	516
FIA - ASTM D-1319 (IBP - 204 °C)				
Saturates (LV %)	89.80			84.70
Olefins (LV %)	0.00			0.00
Aromatics (LV %)	10.20			15.30
Total (LV %)	100.00			100.00
BSG - ASTM D-2549 (204-538 °C)				
Saturates (Wt %)	67.51	48.23	45.91	65.92
Aromatics (Wt %)	30.24	46.25	47.15	31.98
Polar Aromatics (Wt %)	2.25	5.52	6.94	2.10
Total (Wt. %)	100.00	100.00	100.00	100.00
SARA (538 °C Plus)				
Saturates (Wt %)	16.88	16.51	12.85	20.67
Aromatics (Wt %)	58.28	57.63	54.55	58.05
Resins (Wt %)	21.66	20.56	22.26	19.64
Asphaltenes (Wt %)	3.18	5.30	10.34	1.64
Total (Wt %)	100.00	100.00	100.00	100.00

* The sample boiled over and the burn was not complete

Table 4.13 Mass Balance Data for Bonny Light Crude

Based on 100 g of crude oil burned	Bonny Light			
	Crude		5.00 cm Burn	10.00 cm Burn
Weight of residue (g)			9.60	4.70
Weight of solid residue (g)			0.00	0.00
Weight of liquid residue (g)			9.60	4.70
Weight of IBP-204 °C cut (g)	20.61		0.00	0.00
Weight of 204-538 °C cut (g)	71.81		3.98	0.69
Weight of 538 °C plus cut (g)	7.58		5.62	4.01
	@15°C	@40°C		
Amount of saturates in IBP-204 °C (mL)	21.72	21.98	0.00	0.00
Amount of olefins in IBP-204 °C (mL)	0.00	0.00	0.00	0.00
Amount of aromatics in IBP-204°C (mL)	2.47	2.49	0.00	0.00
Weight of saturates in 204-538 °C (g)	5.12		1.92	0.32
Weight of aromatics in 204-538 °C (g)	2.29		1.84	0.33
Weight of polar aromatics in 204-538 °C (g)	0.17		0.22	0.05
Weight of saturates in 538 °C plus (g)	12.12		0.93	0.52
Weight of aromatics in 538 °C plus (g)	41.85		3.24	2.19
Weight of resins in 538 °C plus (g)	15.55		1.16	0.89
Weight of asphaltenes in 538 °C plus (g)	2.28		0.30	0.41
Total saturates (g)			2.85	0.83
Total aromatics (g)			5.08	2.51
Total polar aromatics (g)			0.22	0.05
Total resins (g)			1.16	0.89
Total asphaltenes (g)			0.30	0.41
Composition of Liquid residue				
Saturates (Wt %)			29.66	17.71
Aromatics (Wt %)			52.91	53.46
Polar Aromatics (Wt %)			2.29	1.02
Resins (Wt %)			12.04	18.99
Asphaltenes (Wt %)			3.10	8.82

Table 4.14 Chemical Composition Data for Iranian Heavy Crude

	Iranian Heavy	
	Crude	**5 cm Burn**
Burn Efficiency (%)		93.8
Percent Solid (Wt. %)		4.21
Yield by ASTM D-1160 (Wt. %)		
IBP - 204 °C	20.86	0.00
204 - 538 °C	52.21	13.08
538 °C Plus	26.93	86.92
Total	100.00	100.00
Max. Distillation Temp. Obtained (°C)	538	523
FIA - ASTM D-1319 (IBP - 204 °C)		
Saturates (LV %)	92.20	
Olefins (LV %)	0.00	
Aromatics (LV %)	7.80	
Total (LV %)	100.00	
BSG - ASTM D-2549 (204-538 °C)		
Saturates (Wt %)	59.01	37.10
Aromatics (Wt %)	38.40	57.89
Polar Aromatics (Wt %)	2.59	5.01
Total (Wt. %)	100.00	100.00
SARA (538 °C Plus)		
Saturates (Wt %)	13.78	8.87
Aromatics (Wt %)	51.60	43.26
Resins (Wt %)	16.67	15.25
Asphaltenes (Wt %)	17.95	32.62
Total (Wt %)	100.00	100.00

Table 4.15 Mass Balance Data for Iranian Heavy Crude

Based on 100 g of crude oil burned	Iranian Heavy		
	Crude		5 cm Burn
Weight of residue (g)			6.2
Weight of solid residue (g)			0.26102
Weight of liquid residue (g)			5.93898
Weight of IBP-204 °C cut (g)	20.86		0.00
Weight of 204-538 °C cut (g)	52.21		0.7768186
Weight of 538 °C plus cut (g)	26.93		5.1621614
	@15°C	@40°C	
Amount of saturates in IBP-204 °C (mL)	22.08	22.31	0.00
Amount of olefins in IBP-204 °C (mL)	0.00	0.00	0.00
Amount of aromatics in IBP-204°C (mL)	1.87	1.88	0.00
Weight of saturates in 204-538 °C (g)	30.81		0.2881997
Weight of aromatics in 204-538 °C (g)	20.05		0.4497003
Weight of polar aromatics in 204-538 °C (g)	1.35		0.0389186
Weight of saturates in 538 °C plus (g)	3.71		0.4578837
Weight of aromatics in 538 °C plus (g)	13.90		2.233151
Weight of resins in 538 °C plus (g)	4.49		0.7872296
Weight of asphaltenes in 538 °C plus (g)	4.83		1.6838971
Total saturates (g)			0.7460834
Total aromatics (g)			2.6828513
Total polar aromatics (g)			0.0389186
Total resins (g)			0.7872296
Total asphaltenes (g)			1.6838971
Composition of Liquid residue			
Saturates (Wt %)			12.562484
Aromatics (Wt %)			45.173604
Polar Aromatics (Wt %)			0.655308
Resins (Wt %)			13.2553
Asphaltenes (Wt %)			28.353304

Table 4.16 shows the results for the unburned oil and residues for fresh and weathered evaporated Arabian Light crudes. All the residues contained solids at 163°C, with an apparent trend of increasing solids content with increasing slick thickness and degree of evaporation; none of the residues contained volatiles. Table 4.17 shows the mass balance for the oils and residues calculated on the basis of 100 g of oil burned; it should be noted that the basis for the weathered oil calculations was also 100 g of weathered oil burned. In almost all the residue samples the asphaltenes were preserved; the exception was the 10 cm burn of fresh crude. The reason for this exception is not clear. All residues had high resin and asphaltene contents, explaining their semi-solid nature. Although the trend is not certain, evaporation of the oil prior to the burn appears to have increased the amounts of asphaltenes in the burn residues.

Table 4.18 shows the results of the chemical analyses of the fresh and weathered Mayan crudes and residues. All residue samples contained solids at 163°C; although the trends observed with the Arabian Light are not apparent with this oil. None of the residue samples contained volatile compounds with boiling points less than 204°C. Note that artificially evaporating 22% of the Mayan crude also resulted in the removal of all the volatile material. Table 4.19 shows the data on a per-100 g-burned basis. The mass of asphaltenes remaining in the residues is approximately the same as in the unignited oil for each test. These residues contained very high concentrations of solids, asphaltenes and resins, explaining their near-solid appearance at ambient temperatures.

Table 4.20 presents the results of the chemical analyses of the diesel fuel and burn residues. The residue contained no solids and, like the unburned diesel fuel, the residue contained no higher boiling point fraction (538°C plus fraction). Unlike residues from the crude oil burn, residues from diesel burns did contain some volatiles (IBP to 204°C boiling point fraction). Unlike the crude oils, the diesel residues foamed during the fractional distillation phase of the chemical analysis, thus preventing the separation of the low boiling point fraction from the middle boiling point fraction. Since the residue could not be fractionated: i) the IBP to 204°C fraction was quantified using a simulated distillation procedure (ASTM D-2887); and ii) the saturate/aromatic content of the residue was determined from the residue as a whole by the BSG – ASTM D2549 procedure (see Figure 4.8 and Appendix B). The composition of the residue samples, other than the loss of the small volatile fraction, is very similar to that of the fresh diesel. The complete lack of non-volatile components in the residue samples explains their low viscosity at ambient temperatures. None of the samples contained solid materials. Since most of the crude residue samples contained solids, it appears that these materials are probably precipitates from the heavy ends of the crude as opposed to ash or salt crystals.

A recent review of in-situ burning (Buist *et al.* 1995) suggested a profound lack of information concerning the potential environmental threat posed by residue. The results of the present study provide some important insights into the potential environmental threat posed by residues.

First, the present results confirm that burning has the potential for removing from 70 to 99% of the oil collected in a boom and burn operation.

Table 4.16 Chemical Composition Data for Arabian Light Crude

	Arabian Light				20 % Evap. Arabian Light		31% Evap. Arabian Light	
	Crude	5 cm Burn	10 cm Burn	15 cm Burn	Crude	5 cm Burn	Crude	5 cm Burn
Burn Efficiency (%)		93.5	98.1	87.6		84.0		92.2
Percent Solid (Wt. %)		2.57	3.89	11.99		2.83		7.87
Yield by ASTM D-1160 (Wt. %)								
IBP - 204 °C	18.55	0.00	0.00	0.00	9.07	0.00	2.03	0.00
204 - 538 °C	55.37	9.25	5.26	6.50	61.51	5.35	64.80	8.75
538 °C Plus	26.08	90.75	94.74	93.50	29.54	94.65	33.17	91.25
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Initial Boiling Point (°C)	N/M	304	323	334	N/M	N/M	N/M	N/M
Max. Distillation Temp. Obtained (°C)	538	492	506	485	538	512	538	476
FIA - ASTM D-1319 (IBP - 204 °C)								
Saturates (LV %)	91.90				80.90		80.40	
Olefins (LV %)	0.00				0.00		0.00	
Aromatics (LV %)	8.10				19.10		19.60	
Total (LV %)	100.00				100.00		100.00	
BSG - ASTM D-2549 (204-538 °C)								
Saturates (Wt %)	56.78	36.52	38.54	36.08	56.81	39.01	56.45	37.58
Aromatics (Wt %)	41.14	60.64	58.53	61.20	40.96	57.67	41.43	59.33
Polar Aromatics (Wt %)	2.08	2.84	2.93	2.72	2.23	3.32	2.12	3.09
Total (Wt. %)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
SARA (538 °C Plus)								
Saturates (Wt %)	14.29	8.78	8.40	7.44	14.29	8.08	14.84	7.29
Aromatics (Wt %)	54.81	48.58	45.11	43.52	54.40	40.39	54.60	43.15
Resins (Wt %)	13.29	11.29	9.52	8.54	12.77	10.03	11.57	9.91
Asphaltenes (Wt %)	17.61	31.35	36.97	40.50	18.54	41.50	18.99	39.65
Total (Wt %)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 4.17 Mass Balance Data for Arabian Light Crude

Based on 100 g of crude oil burned	Arabian Light				20% Evap. Arabian Light		31% Evap. Arabian Light	
	Crude	5 cm Burn	10 cm Burn	15 cm Burn	Crude	5 cm Burn	Crude	5 cm Burn
Weight of residue (g)		6.5	1.9	12.4		16		7.8
Weight of solid residue (g)		0.16	0.07	1.48		0.45		0.61
Weight of liquid residue (g)		6.33	1.82	10.91		15.54		7.18
Weight of IBP-204 °C cut (g)	18.55	0.00	0.00	0.00	9.07	0.00	2.03	0.00
Weight of 204-538 °C cut (g)	55.37	0.58	0.09	0.70	61.51	0.83	64.8	0.62
Weight of 538 °C plus cut (g)	26.08	5.74	1.73	10.20	29.42	14.71	33.17	6.55
	@15°C @40°C				@15°C @40°C		@15°C @40°C	
Amount of saturates in IBP-204 °C (mL)	19.59 19.82	0.00	0.00	0.00	8.08 8.16	0.00	1.76 1.78	0.00
Amount of olefins in IBP-204 °C (mL)	0.00 0.00	0.00	0.00	0.00	0.00 0.00	0.00	0.00 0.00	0.00
Amount of aromatics in IBP-204°C (mL)	1.72 1.74	0.00	0.00	0.00	1.90 1.92	0.00	0.42 0.43	0.00
Weight of saturates in 204-538 °C (g)	31.43	0.21	0.03	0.25	34.94	0.32	36.57	0.23
Weight of aromatics in 204-538 °C (g)	22.77	0.35	0.05	0.43	25.19	0.47	26.84	0.37
Weight of polar aromatics in 204-538 °C (g)	1.15	0.01	0.00	0.01	1.37	0.02	0.39	0.01
Weight of saturates in 538 °C plus (g)	3.72	0.50	0.14	0.75	4.20	1.18	4.92	0.47
Weight of aromatics in 538 °C plus (g)	14.29	2.79	0.78	4.44	16.00	5.94	18.11	2.82
Weight of resins in 538 °C plus (g)	3.46	0.64	0.16	0.87	3.75	1.47	3.83	0.64
Weight of asphaltenes in 538 °C plus (g)	4.59	1.80	0.63	4.13	5.45	6.10	6.29	2.59
Total saturates (g)		0.71	0.18	1.01		1.51		0.71
Total aromatics (g)		3.14	0.83	4.87		6.42		3.20
Total polar aromatics (g)		0.01	0.00	0.01		0.02		0.01
Total resins (g)		0.64	0.16	0.87		1.47		0.64
Total asphaltenes (g)		1.80	0.63	4.13		6.10		2.59
Composition of Liquid residue								
Saturates (Wt %)		11.34	9.98	9.30		9.73		9.94
Aromatics (Wt %)		49.69	45.81	44.66		41.31		44.56
Polar Aromatics (Wt %)		0.26	0.15	0.17		0.17		0.27
Resins (Wt %)		10.24	9.01	7.98		9.49		9.04
Asphaltenes (Wt %)		28.45	35.02	37.86		39.27		36.18

Table 4.18 Chemical Composition Data for Mayan Crude

	Mayan				12 % Evap. Mayan		22% Evap. Mayan	
	Crude	5 cm Burn	10 cm Burn	15 cm Burn	Crude	5 cm Burn	Crude	5 cm Burn
Burn Efficiency (%)		75.1	74.3	71.1		72.2		70.3
Percent Solid (Wt. %)		12.75	4.76	8.09		3.43		9.00
Yield by ASTM D-1160 (Wt. %)								
IBP - 204 °C	14.23	0.00	0.00	0.00	7.37	0.00	0.00	0.00
204 - 538 °C	45.58	9.02	14.15	13.07	49.29	6.47	50.23	3.19
538 °C Plus	40.19	90.98	85.85	86.93	43.34	93.53	49.77	96.81
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Initial Boiling Point (°C)	N/M	343	343	303	N/M	284	N/M	320
Max. Distillation Temp. Obtained (°C)	529	486	514	516	538	467	536	412
FIA - ASTM D-1319 (IBP - 204 °C)								
Saturates (LV %)	91.90				83.50			
Olefins (LV %)	0.00				0.00			
Aromatics (LV %)	8.10				16.50			
Total (LV %)	100.00				100.00			
BSG - ASTM D-2549 (204-538 °C)								
Saturates (Wt %)	51.31	34.48	34.47	33.48	50.67	32.85	51.51	43.60
Aromatics (Wt %)	46.24	60.99	61.00	61.51	46.29	63.64	45.59	54.51
Polar Aromatics (Wt %)	2.45	4.35	4.53	5.01	3.04	3.51	2.90	1.89
Total (Wt. %)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
SARA (538 °C Plus)								
Saturates (Wt %)	6.84	5.36	5.39	5.23	6.91	4.49	7.05	4.73
Aromatics (Wt %)	44.44	34.23	34.43	32.40	41.82	30.92	43.08	29.59
Resins (Wt %)	13.39	9.82	12.87	11.15	15.27	12.97	12.09	8.28
Asphaltenes (Wt %)	35.33	50.59	47.31	51.22	36.00	51.62	37.78	57.40
Total (Wt %)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 4.19 Mass Balance Data for Mayan Crude

Based on 100 g of crude oil burned	Mayan				12 % Evap. Mayan		22% Evap. Mayan	
	Crude	5 cm Burn	10 cm Burn	15 cm Burn	Crude	5 cm Burn	Crude	5 cm Burn
Weight of residue (g)		24.9	25.7	28.9		27.8		29.7
Weight of solid residue (g)		3.17	1.22	2.33		0.95		2.67
Weight of liquid residue (g)		21.72	24.47	26.56		26.84		27.02
Weight of IBP-204 °C cut (g)	14.23	0.00	0.00	0.00	7.37	0.00	0.00	0.00
Weight of 204-538 °C cut (g)	45.58	1.95	3.46	3.47	49.29	1.73	50.23	0.86
Weight of 538 °C plus cut (g)	40.19	19.76	21.01	23.09	43.34	25.10	49.77	26.16
	@15°C @40°C				@15°C @40°C			
Amount of saturates in IBP-204 °C (mL)	14.06 14.13	0.00	0.00	0.00	7.11 7.19	0.00	0.00	0.00
Amount of olefins in IBP-204 °C (mL)	0.00 0.00	0.00	0.00	0.00	0.00 0.00	0.00	0.00	0.00
Amount of aromatics in IBP-204°C (mL)	1.23 1.24	0.00	0.00	0.00	0.62 0.63	0.00	0.00	0.00
Weight of saturates in 204-538 °C (g)	23.38	0.67	1.19	1.16	25.29	0.57	25.77	0.37
Weight of aromatics in 204-538 °C (g)	21.07	1.19	2.11	2.13	22.79	1.10	23.22	0.47
Weight of polar aromatics in 204-538 °C (g)	1.11	0.08	0.15	0.17	1.20	0.06	1.23	0.01
Weight of saturates in 538 °C plus (g)	2.74	1.05	1.13	1.20	2.96	1.12	3.40	1.23
Weight of aromatics in 538 °C plus (g)	17.86	6.76	7.23	7.48	19.26	7.76	22.11	7.74
Weight of resins in 538 °C plus (g)	5.38	1.94	2.70	2.57	5.80	3.25	6.66	2.16
Weight of asphaltenes in 538 °C plus (g)	14.19	9.99	9.94	11.82	15.31	12.96	17.58	15.01
Total saturates (g)		1.73	2.32	2.36		1.69	29.17	1.61
Total aromatics (g)		7.96	9.34	9.61		8.86	45.34	8.21
Total polar aromatics (g)		0.08	0.15	0.17		0.06	1.23	0.01
Total resins (g)		1.94	2.70	2.57		3.25	6.66	2.16
Total asphaltenes (g)		9.99	9.94	11.82		12.96	17.58	15.01
Composition of Liquid residue								
Saturates (Wt %)		7.98	9.50	8.92		6.32	29.17	5.97
Aromatics (Wt %)		36.64	38.18	36.20		33.03	45.34	30.38
Polar Aromatics (Wt %)		0.39	0.64	0.65		0.22	1.23	0.06
Resins (Wt %)		8.93	11.04	9.69		12.13	6.66	8.01
Asphaltenes (Wt %)		46.02	40.61	44.52		48.28	17.58	55.56

Table 4.20 Chemical Composition Data for Diesel

	Diesel			
	Crude	5 cm Burn	10 cm Burn	15 cm Burn
Burn Efficiency (%)		98.6	99.3	99.7
Percent Solid (Wt. %)		0.00	0.00	0.00
Yield by ASTM D-1160 (Wt. %)				
IBP - 204 °C	18.30	1.35	1.80	4.38
204 - 538 °C	81.70	98.65	98.20	95.62
538 °C Plus	0.00	0.00	0.00	0.00
Total	100.00	100.00	100.00	100.00
Max. Distillation Temp. Obtained (°C)	400+	400+	400+	400+
FIA - ASTM D-1319 (IBP - 204 °C)				
Saturates (LV %)	81.2			
Olefins (LV %)	0.5			
Aromatics (LV %)	18.3			
Total (LV %)	100.00			
BSG - ASTM D-2549 (204-538 °C)				
Saturates (Wt %)	70.41	64.09	63.30	62.17
Aromatics (Wt %)	29.04	34.70	35.17	36.21
Polar Aromatics (Wt %)	0.55	1.21	1.53	1.62
Total (Wt. %)	100.00	100.00	100.00	100.00

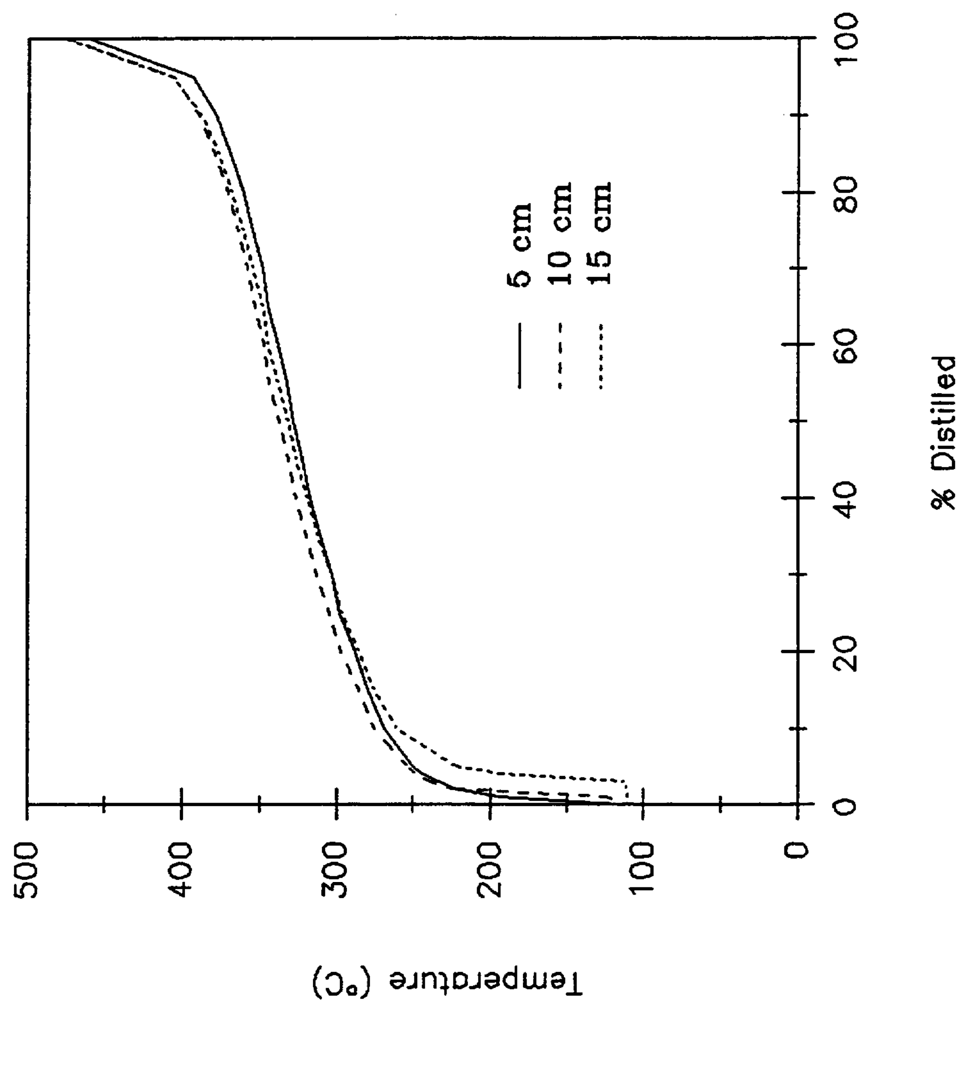

Figure 4.8 Diesel burn residue distillation curves

Second, for most oils tested, burn residues increased in density to the point where they would sink in both fresh water and seawater. This may be cause for concern because the sinking burn residue fragments will settle to the seabed in the vicinity of the burn. In a large spill, a sizable amount of burn residue may accumulate on the seabed near the spill site and may pose environmental problems depending on its properties and composition.

Third, the present work provides general information concerning the stickiness of residues. Stickiness is of interest from the point of view of potential effects in marine birds. In this study, the residue from the heavier oils (Mayan, Arabian Heavy and Iranian Heavy crudes) formed brittle, non-sticky residue that would probably not adhere to birds' feathers and hence could pose little risk to them. The lighter oils, however, did yield sticky residues that might adhere to bird feathers and might be ingested during preening. (It might be considered that the sticky burn residue may be academic since almost all of the residues generated in this study would sink in both fresh and salt water. However, real-world burns may be less efficient than those conducted under ideal conditions in this study so that some residues, at least of lighter crudes, might be expected to float.)

Fourth, this study has provided some very useful information concerning the fate of aromatic hydrocarbons (which includes the polynuclear aromatic hydrocarbons – PAHs) during in-situ burns. The data in Tables 4.6 to 4.19 show that in these tests burning has stripped all or most of the low and middle-range boiling point aromatic compounds from the residue, but has concentrated the higher boiling point aromatics in the residue. Virtually all of the lower boiling point aromatics (BP < 204°C) have been stripped from the residue. Burning has greatly reduced both the amount and concentration of the middle boiling point fraction (204°C BP > 538°C), which include 2- to 5-ring aromatic compounds, including mutagenic compounds such as benzopyrenes. In all cases, however, some of the mid-range fraction persists in the residue. For all crude oils, some of the larger aromatics (BP > 538°C) are removed from the residue, but in all cases, the concentration of these compounds in the residue is dramatically increased over the parent oil because of the selective removal of the lower boiling point fractions. Indeed in all cases, the high boiling point aromatics are the second most abundant components of the residue next to asphaltenes. This may or may not pose environmental problems depending on the biological activity of these high BP aromatics.

Regardless of whether burn residue floats or sinks, the presence of PAHs in burn residues will continue to cause concern. The potential environmental threat posed by PAHs will depend on the species of compounds that persist in the residue, their biological activity, and bioavailability from the semi-solid residue. The next logical step in addressing this threat is to identify the chemical constituents of the aromatic fraction of the burn residue. Subsequent work should include some general tests to assess the biological activity of the fraction and to assess bioavailability of those constituents from the semi-solid residue matrix.

5.0 Conclusions and Recommendations

5.1 Conclusions

The following conclusions have been drawn:

1) Residues from efficient batch-type burns of thick slicks of heavier crudes can sink in fresh or salt water.

2) The rheology of residues from efficient, batch-type burns of thick slicks of crudes is semi-solid or solid at ambient temperatures.

3) The residue from burns of automotive diesel fuel is not very different rheologically or chemically from the original fuel and will not sink in fresh or salt water.

4) Evaporation of a crude oil prior to burning results in a more dense residue.

5) The process occurring during in-situ burning appears to be an imperfect Equilibrium Flash Vaporization that results in the progressive concentration of the heavier non-volatile compounds of the crude in the residue. This concentration process results in increases in residue density and explains the semi-solid or near-solid rheology of the residue.

6) Samples of the residues from most of the crude oil burn tests contained significant amounts of solids (at 163°C). The source of this solid material may be precipitation of very heavy ends of the crude as a result of the concentration process occurring during the imperfect Equilibrium Flash Vaporization. The only residue samples that did not contain solids were from the diesel and Bonny Light burns.

7) None of the burn residue from crude oils contained any volatiles (with boiling points up to 204°C or approximately C_{12}); all contained some portion of the medium volatility compounds (boiling points between 204°C and 538°C). The majority of the residues were composed of non-volatile compounds with boiling points greater than 538°C.

8) For most of the crudes, the asphaltenes appeared to be preserved and concentrated into the burn residue. Asphaltenes and resins were the main component of most crude burn residue samples and this, in conjunction with the high solids content of these same residue samples, is believed to be responsible for the semi-solid and near-solid rheology of the residues at ambient temperatures.

9) The ratio of the density of the residue to that of the original oil appears to correlate with the amount of slick burned, represented by the product of the volume fraction burned and the initial slick thickness. The following preliminary mathematical model has been proposed to represent the data:

$$\rho/\rho_o = 1 + C_1(1 - \exp(-C_2 F_{BV} X_o))$$

with $C_2 = 0.33\ cm^{-1}$; and,
$C_1 = 0.2$ for crudes
$= 0.07$ for automotive diesel

5.2 Recommendations

1) Further testing needs to be undertaken to explore the effects of scale (i.e., fire size) on burn residue properties.

2) Simple studies should be undertaken to determine the potential environmental threat posed by burn residue samples from this study, including the following:

   a) identify the most abundant constituents of the aromatic fractions of the residue;

   b) conduct simple tests to determine the biological activity of the major constituent fractions; and

   c) if any fraction displays significant biological activity, assess the bioavailability of potential causative compounds from the semi-solid residue matrix. Biological activity and bioavailability tests should consider both residues ingested by seabirds and those that settle to the seafloor and may pose a threat to seabed communities.

6.0 References

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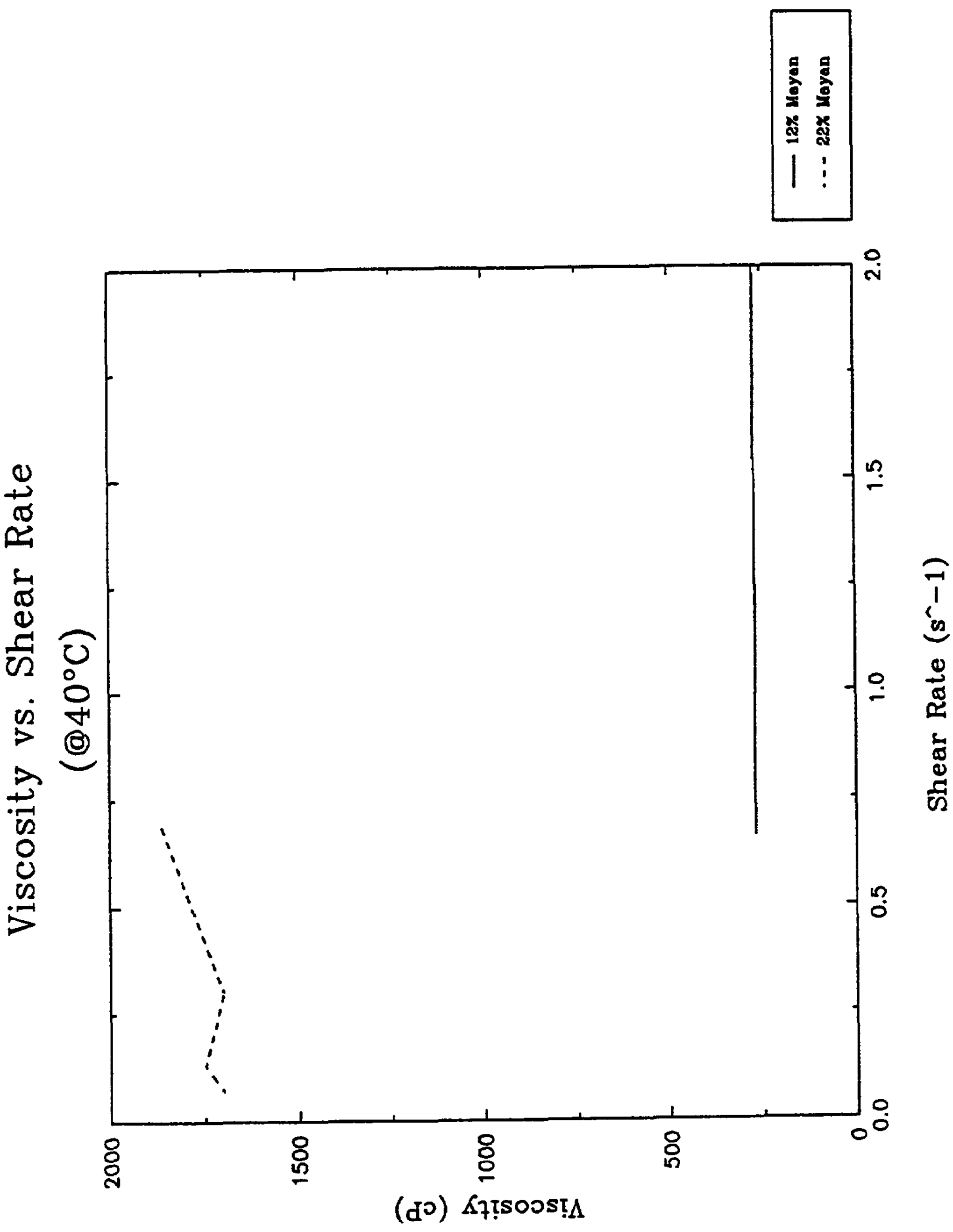
Appendix A

Test Burn Data

Test Burn Data

Oil	Thickness (cm)	Date	File	Air T (C)	Water T (C)	Oil Mass (kg)	Residue Mass (kg)	Preheat Time min:sec	Ignition Time min:sec	Intense Burn Time hr:min:sec	Extinction Time hr:min:sec	Comments
Diesel	5	12/08/94	DIES_05	20.0	10.0	5.3495	0.0815	00:00	00:00	24:45	26:12	ignition - 100mL gasoline
Diesel	5	12/12/94	DIES_052	12.8	7.7	5.3495	0.0748	1:10	1:15	24:30	25:39	ignition - ignited floating sorbent pad
Diesel	10	12/13/94	DIES_10	11.0	14.1	10.6990	0.0648	00:00	00:00	44:00	45:21	ignition - 1) sorbent set on fire, went out; 2) 100mL gasoline
Diesel	10	12/14/94	DIES_10b	1.0	10.5	10.6990	0.0715	00:00	00:00	47:48	49:20	ignition - 1) sorbent ignited; 2) 100mL gasoline
Diesel	15	12/15/94	DIES_15	13.0	11.3	16.0485	0.0548	00:00	00:00	1:04:46	1:05:47	ignition - 1) sorbent ignited; 2) 100mL gasoline
ANS	5	12/15/94	ANS_05	20.0	14.9	5.7200	0.8653	00:00	13:00	-	57:02	ignition - blow torch, flame went out at 54:43 (5mm down); residue - brittle solid, strong odou
ANS	10	12/21/94	ANS_10	10.0	11.0	9.6800	0.9590	00:03	00:21	1:37:10	1:38:32	ignition - torch, vigorous burn, splash over, 1:35:44 - more vigorous burning stage in middle
ANS	15	02/10/95	ANS_15	12.5	13.6	16.6798	1.5112	00:00	00:18	2:11:00	2:15:46	
Bonny Lt.	5	12/16/94	BOLT_05	18.0	10.8	5.5380	0.5339	00:00	00:03	41:20	42:03	ignition - torch; taffy like semi-solid formed, very sticky, buoyant
Bonny Lt.	10	12/16/94	BOLT_10	21.5	14.5	11.0760	0.5229	00:00	00:11	1:33:11	1:33:34	ignition - torch; flashing during intense burn
Bonny Lt.	15	12/19/94	BOLT_15	20.5	6.9	16.6140	-	00:00	00:03	-	-	ignition - torch; oil warmed to melt precipitates (to 26C); 25:00 - spill over (flame extiguished
Mayan	5	02/08/95	MAYA_05	15.9	15.6	6.0450	1.5076	00:00	00:39	42:50	49:58	NB: 44:10 - unburnable residue formed started to smother flames
Mayan	10	02/08/95	MAYA_10	14.7	16.3	11.5523	2.9736	00:00	00:39	1:26:50	1:34:14	
Mayan	15	02/28/95	MAYA_15	14.9	15.0	17.4074	5.0367	00:00	00:32	2:17:56	2:24:00	
Arab. Hvy.	5	02/09/95	AHeav_05	11.4	11.6	3.6492	0.9066	00:00	00:00	45:47	49:08	
Arab. Hvy.	10	02/09/95	AHeav_10	16.4	13.6	10.9657	1.9454	00:00	00:16	1:28:00	1:32:00	
Arab. Hvy.	15	03/02/95	AHeav_15	15.9	12.9	16.9370	3.0000	00:00	00:10	2:24:00	2:33:51	NB: 1:50 - flares, popping, hissing, thick black smoke visible; 2:17 - flares growing, louder cr
Arab. Lt.	5	03/01/95	ALight_05	14.5	17.2	5.4436	0.3515	00:00	00:00	47:00	50:40	
Arab. Lt.	10	03/02/95	ALight_10	15.0	11.5	11.0041	0.2099	00:00	00:00	1:39:00	1:42:31	
Arab. Lt.	15	03/02/95	ALight_15	12.8	11.1	15.9465	1.9795	00:00	00:03	2:24:20	2:28:09	
ASMB	5	04/12/95	ASMB_05	15.3	16.8	5.7553	0.6638	00:00	00:05	36:00	37:40	NB: vigorous phase appeared to foam out, flames went into hood
ASMB	10	04/12/95	ASMB_10	16.5	18.7	11.2469	0.3016	00:00	00:07	1:21:00	1:23:30	NB: high flames at base of hood, foaming appeared
ASMB	15	04/12/95	ASMB_15	13.2	13.3	16.3090	0.5847	00:00	00:05	1:55:00	1:58:23	NB: flames to base of hood from start of burn, 115:00 - burn spitting, popping
Iranian Hv	5	03/01/95	IRHeav_0	15.3	13.2	5.5079	0.3428	00:00	00:14	40:20	43:20	NB: during 1st 11 minutes, flames reached base of fume hood, very intense burn
12% Maya	5	03/02/95	MAYA12	17.6	12.9	6.3963	1.7764	00:18	00:42	47:00	52:29	NB: propane torch insufficient to light slick, flame height 1/3 to hood, bubbling
20% Arab	5	04/11/95	ALt20_05	15.6	15.6	5.9883	0.9564	00:28	N/M	1:04:28	1:06:06	NB: oil did not ignite w/ torch, eventually 1L diesel used w/ sorbent; intense burn, flames hig
31% Arab	5	04/13/95	ALt31_05	12.6	12.6	6.1176	0.4780	00:00	00:06	58:00	1:02:07	NB: 100mL diesel + triangular sorbent pad finally ignited slick; flames halfway to hood
22% Maya	5	04/13/95	MAYA22	13.5	20.0	6.2032	1.8420	00:10	1:06	47:00	54:43	NB: strong flames 3/4 way to hood, popping, hissing, spattering, torch ignition only


Viscosity vs. Shear Rate
(@40°C)
Viscosity (cP)
Shear Rate (s^-1)
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1500
1000
500
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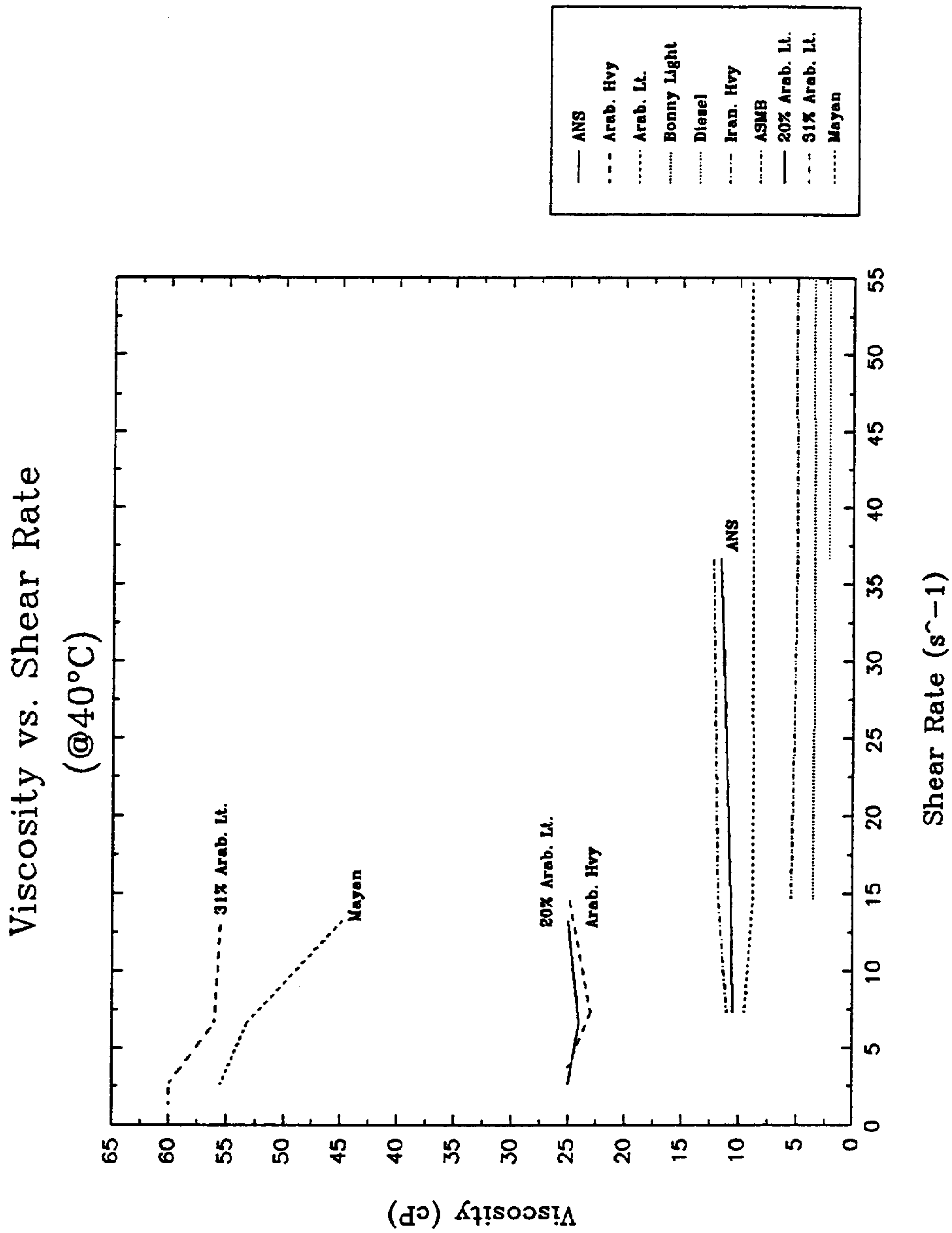
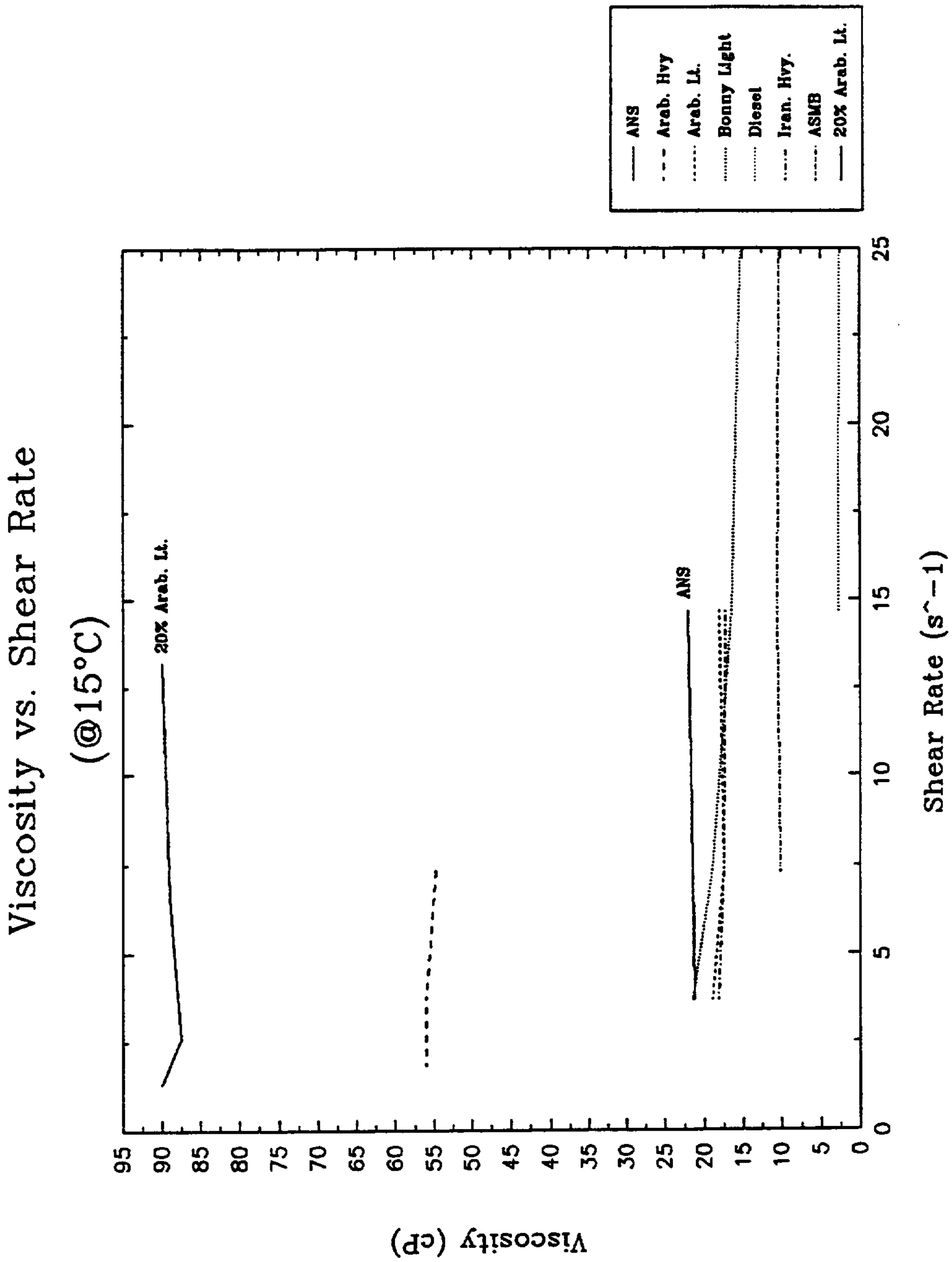
0.0
0.5
1.0
1.5
2.0
12% Meyan
22% Meyan


Viscosity vs. Shear Rate
(@40°C)
Viscosity (cP)
Shear Rate (s^-1)
31% Arab. Lt.
Mayan
20% Arab. Lt.
Arab. Hvy
ANS
ANS
Arab. Hvy
Arab. Lt.
Bonny Light
Diesel
Iran. Hvy
ASMB
20% Arab. Lt.
31% Arab. Lt.
Mayan


Viscosity vs. Shear Rate
(@15°C)
Viscosity (cP)
Shear Rate (s^-1)
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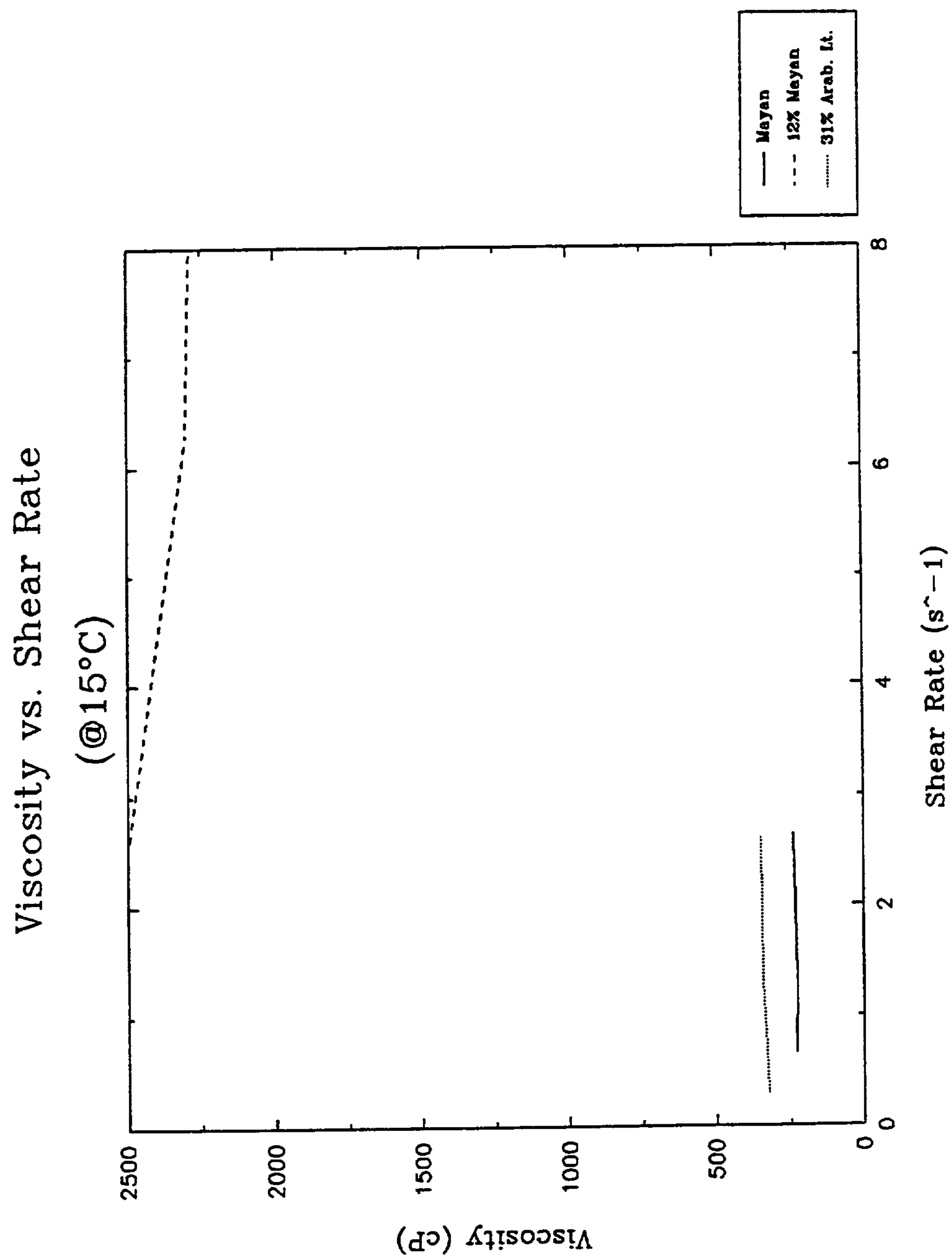
Arab. Hvy
Arab. Lt.
Bonny Light
Diesel
Iran. Hvy.
ASMB
20% Arab. Lt.


Viscosity vs. Shear Rate
(@15°C)
Viscosity (cP)
Shear Rate (s^-1)
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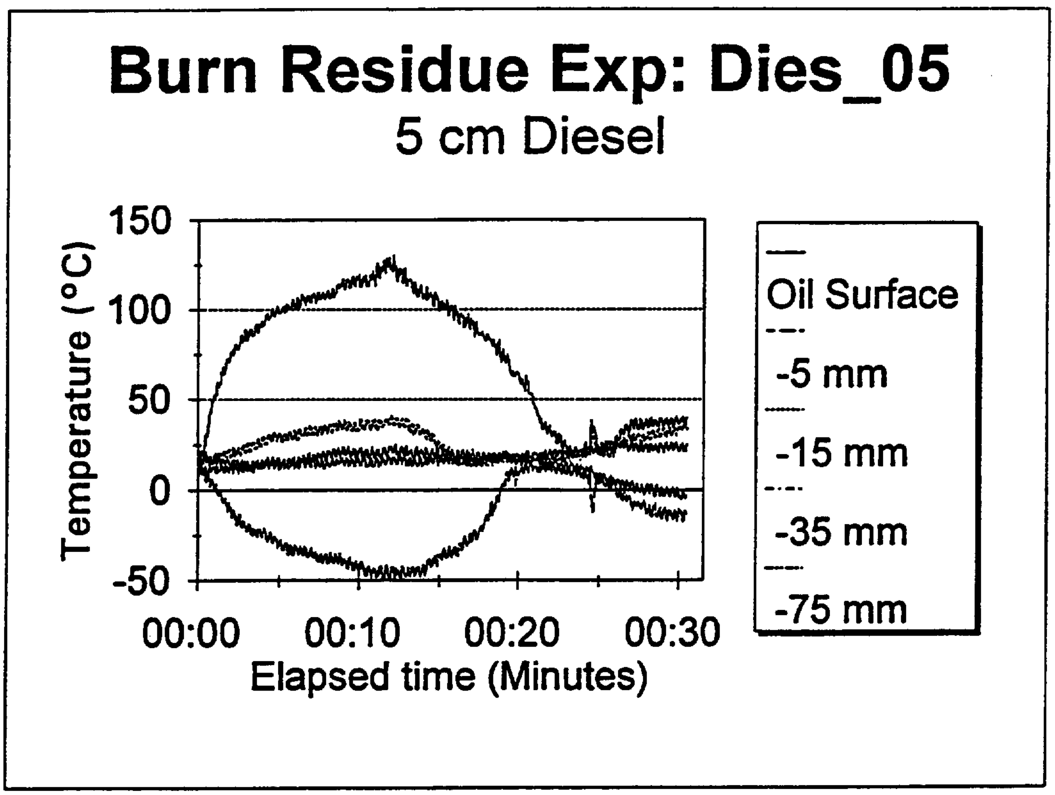
2000
1500
1000
500
0
0
2
4
6
8
Mayan
12% Mayan
31% Arab. Lt.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Temperature (°C)
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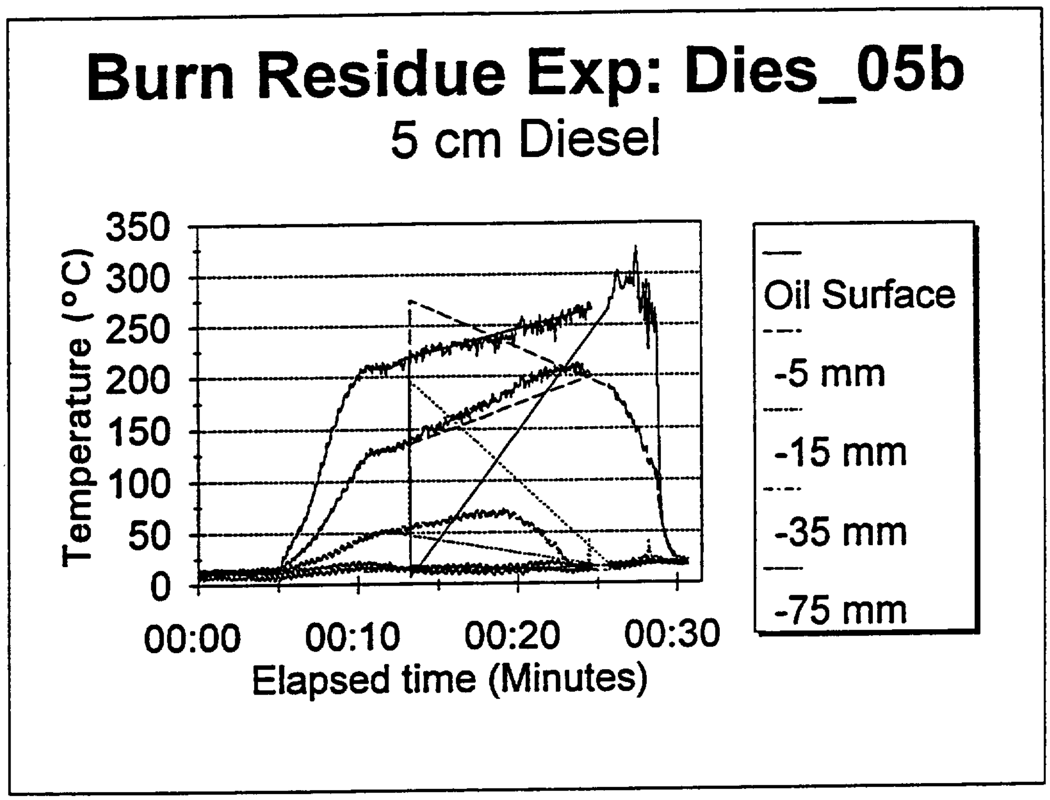
100
50
0
-50
00:00
00:10
00:20
00:30
Elapsed time (Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm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5 cm Diesel
Temperature (°C)
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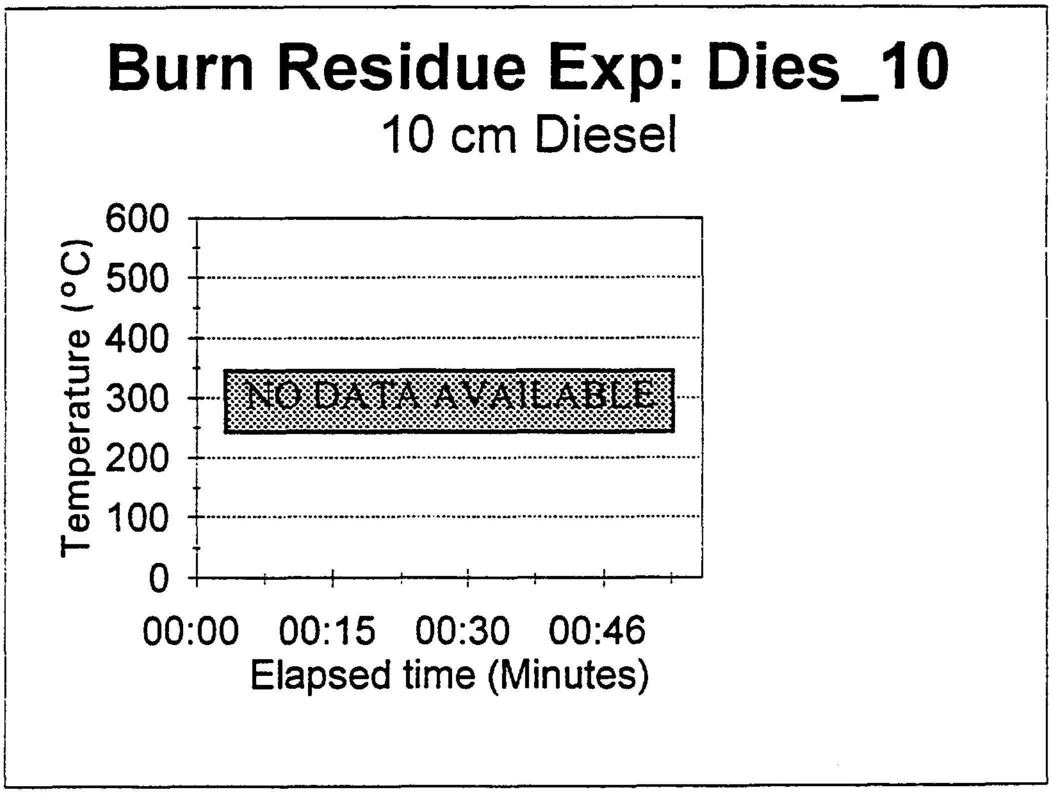
300
250
200
150
100
50
0
00:00
00:10
00:20
00:30
Elapsed time (Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm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Temperature (°C)
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400
300
200
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00:00
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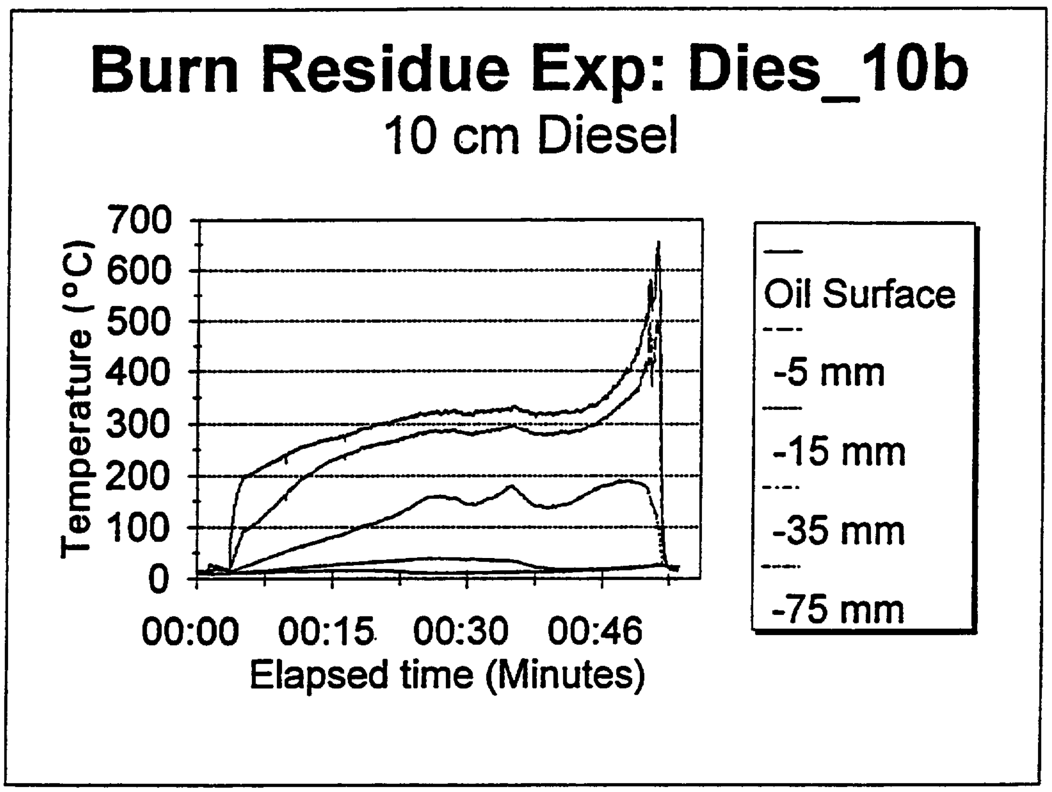
00:46
Elapsed time (Minutes)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10 cm Diesel
700
600
500
400
300
200
100
0
Temperature (°C)
00:00
00:15
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Elapsed time (Minutes)
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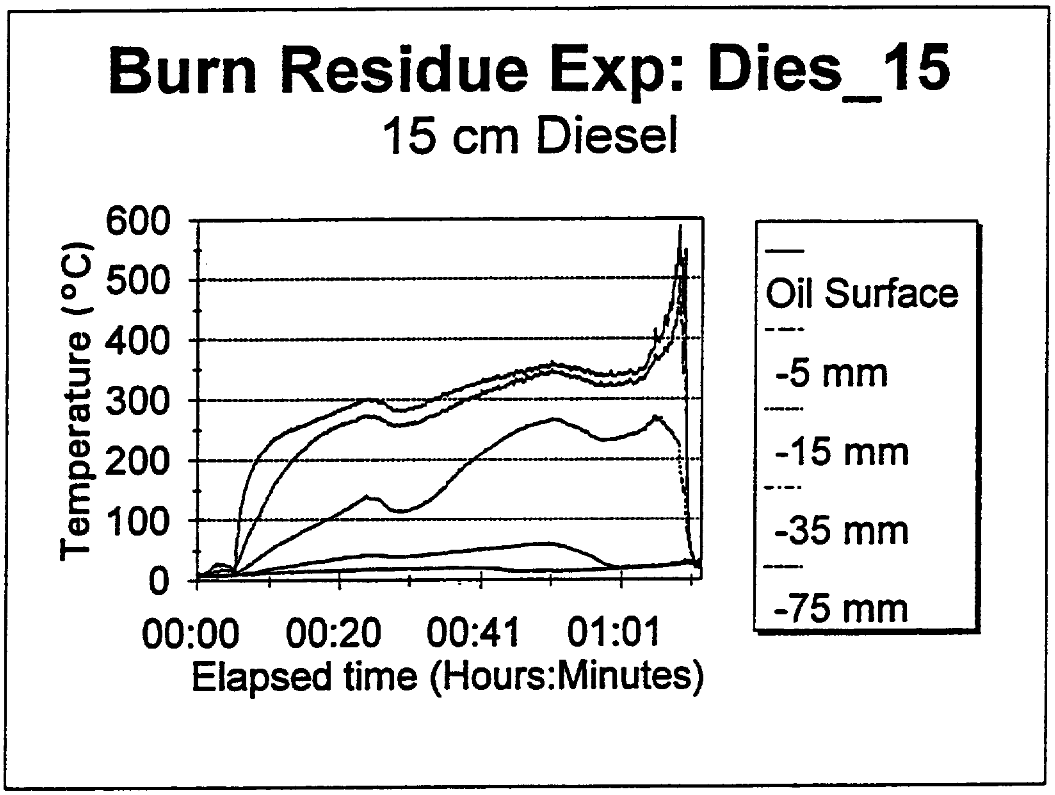
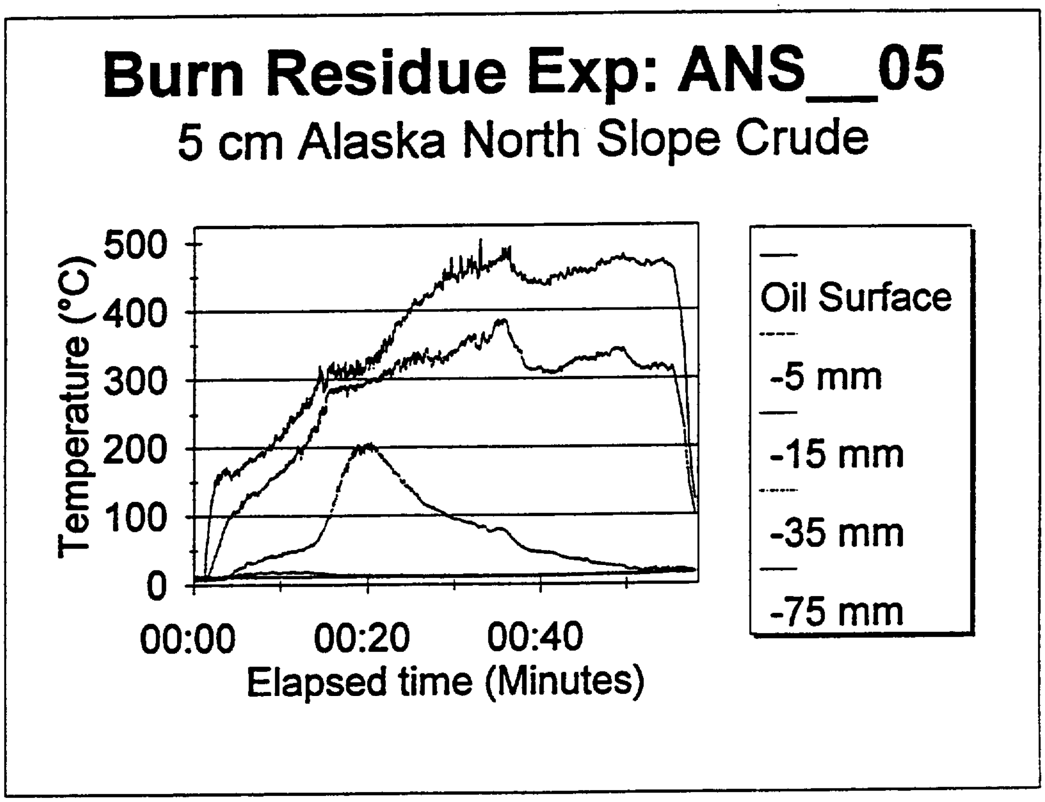
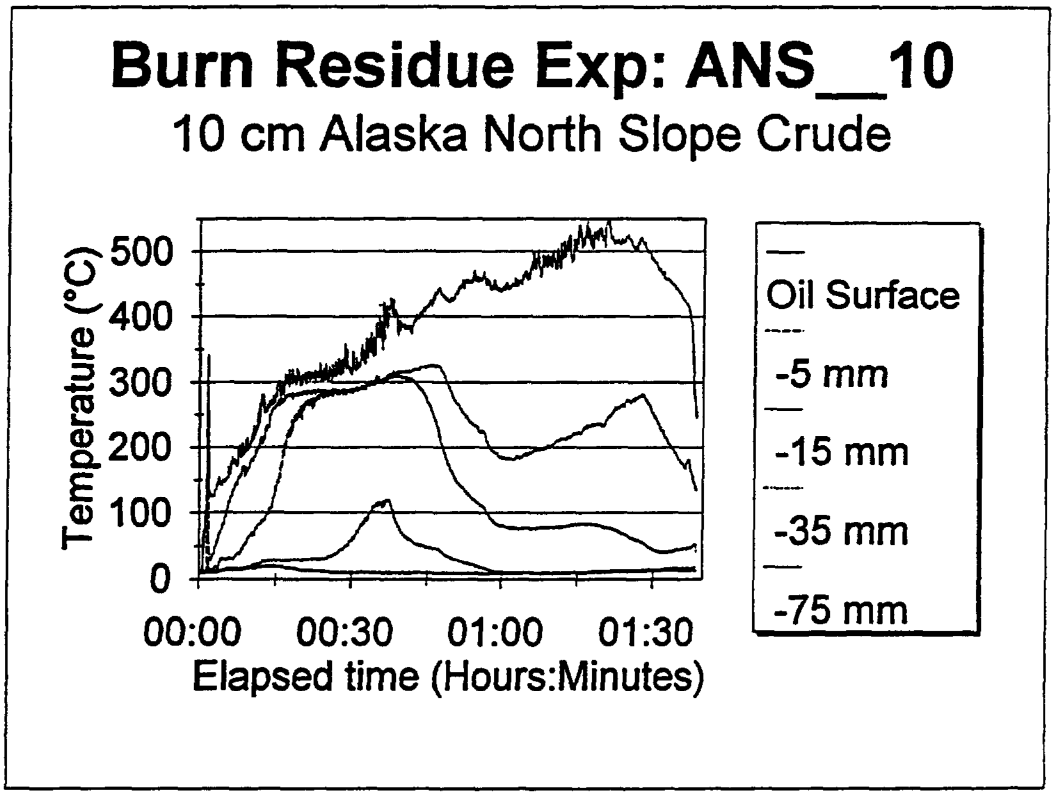
-15 mm
-35 mm
-75 mm



Burn Residue Exp: Dies_15
15 cm Diesel
Temperature (°C)
600
500
400
300
200
100
0
00:00
00:20
00:41
01:01
Elapsed time (Hours:Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm


Burn Residue Exp: ANS__05
5 cm Alaska North Slope Crude
Temperature (°C)
500
400
300
200
100
0
00:00
00:20
00:40
Elapsed time (Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm



Burn Residue Exp: ANS__10
10 cm Alaska North Slope Crude
Temperature (°C)
500
400
300
200
100
0
00:00
00:30
01:00
01:30
Elapsed time (Hours:Minutes)
Oil Surface
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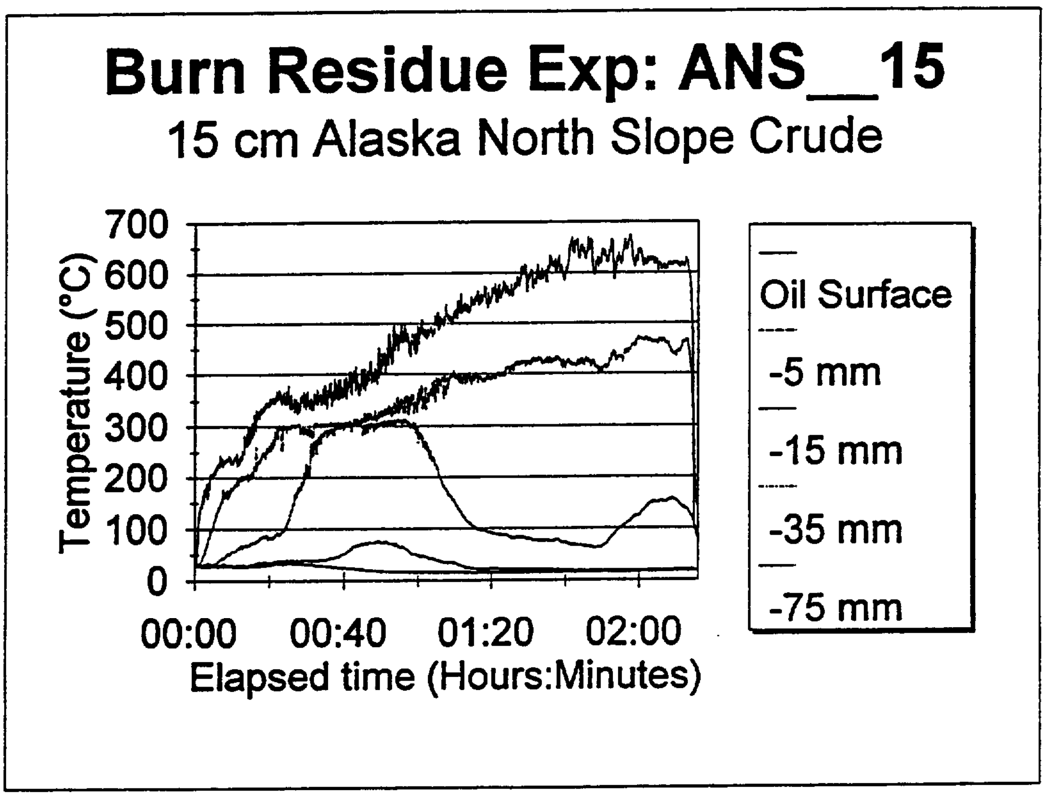
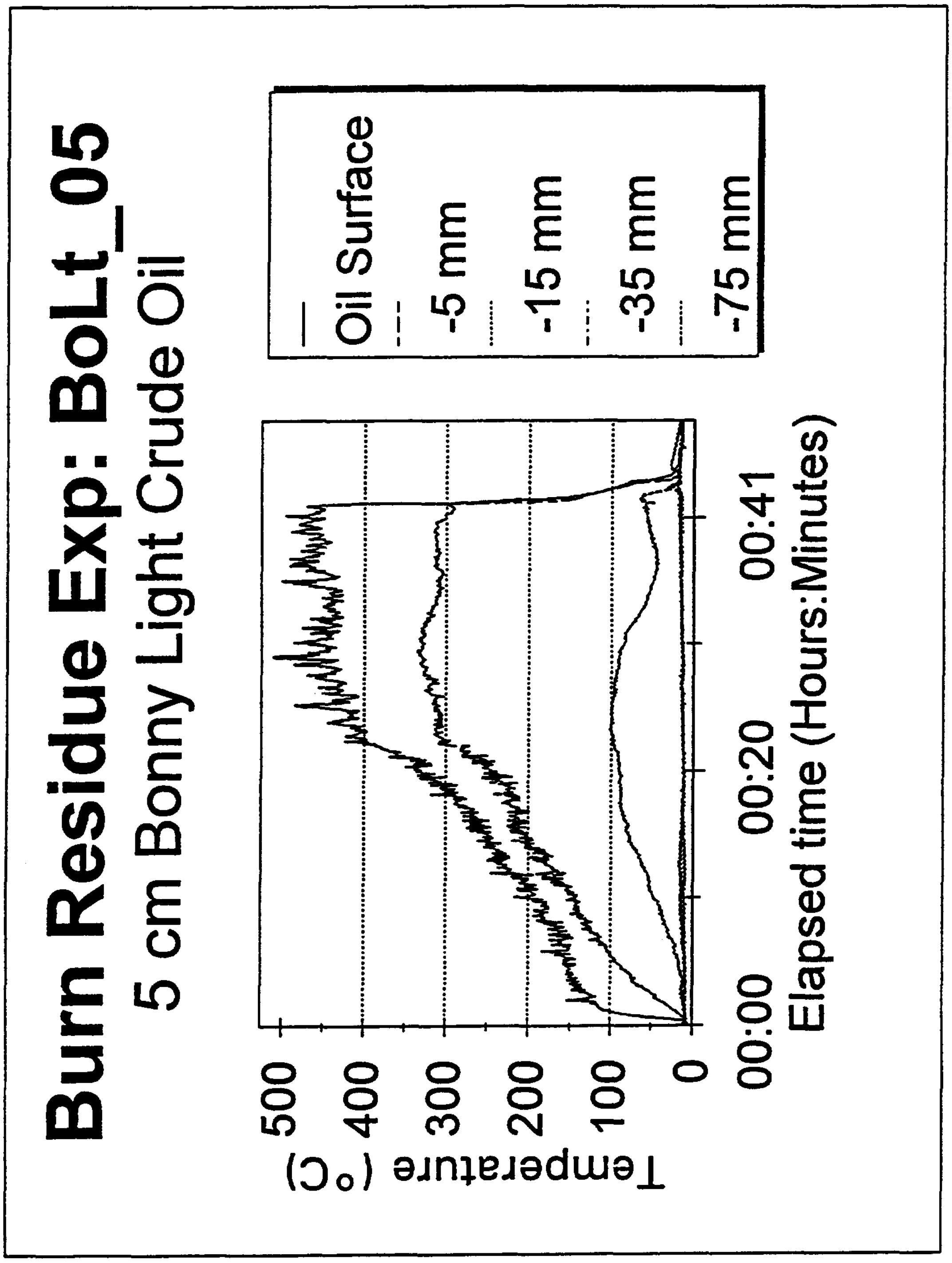
-15 mm
-35 mm
-75 mm



Burn Residue Exp: ANS__15
15 cm Alaska North Slope Crude
Temperature (°C)
700
600
500
400
300
200
100
0
00:00
00:40
01:20
02:00
Elapsed time (Hours:Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm


Burn Residue Exp: BoLt_05
5 cm Bonny Light Crude Oil
Temperature (°C)
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400
300
200
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0
00:00
00:20
00:41
Elapsed time (Hours:Minutes)
Oil Surface
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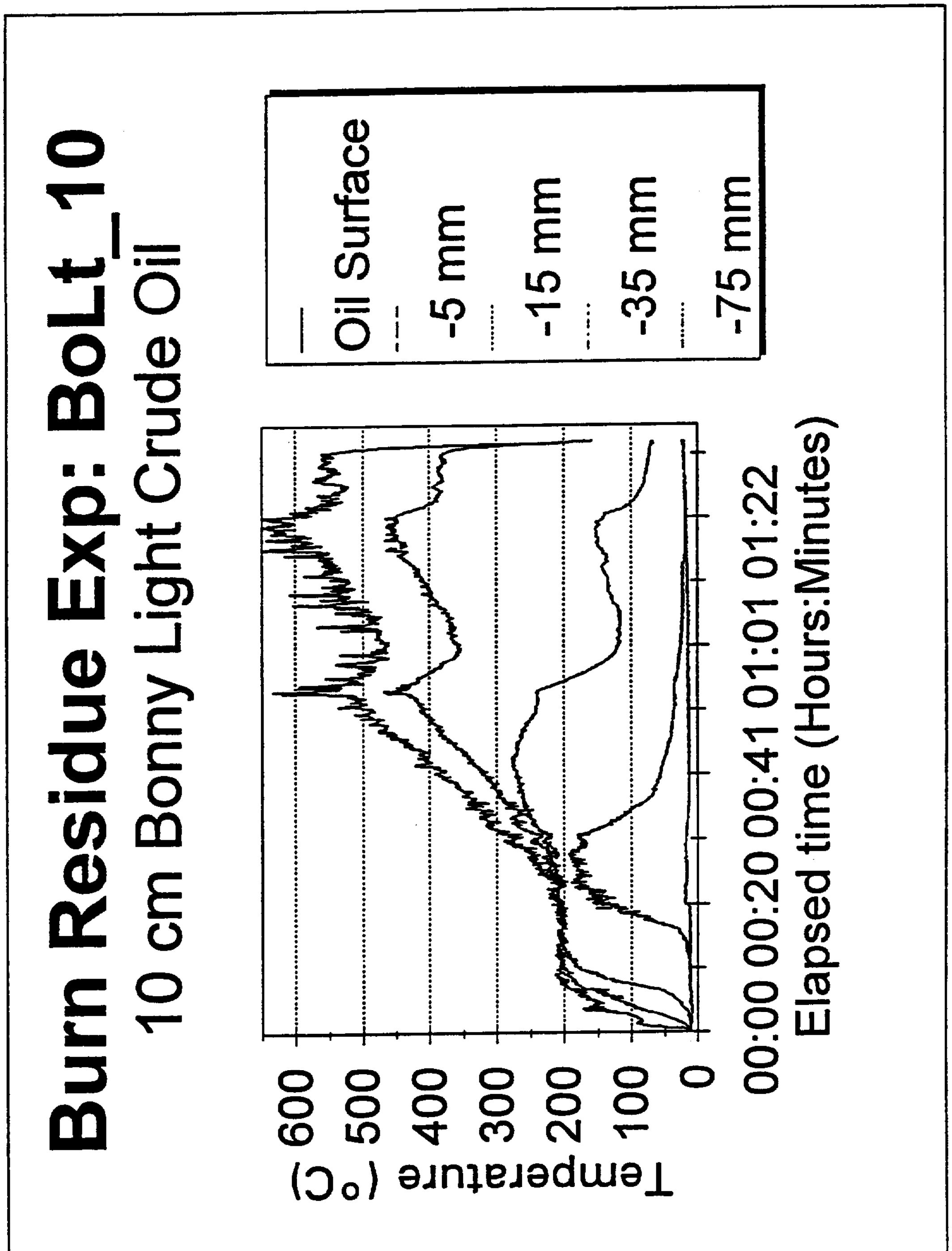
-15 mm
-35 mm
-75 mm


Burn Residue Exp: BoLt_10
10 cm Bonny Light Crude Oil
Temperature (°C)
600
500
400
300
200
100
0
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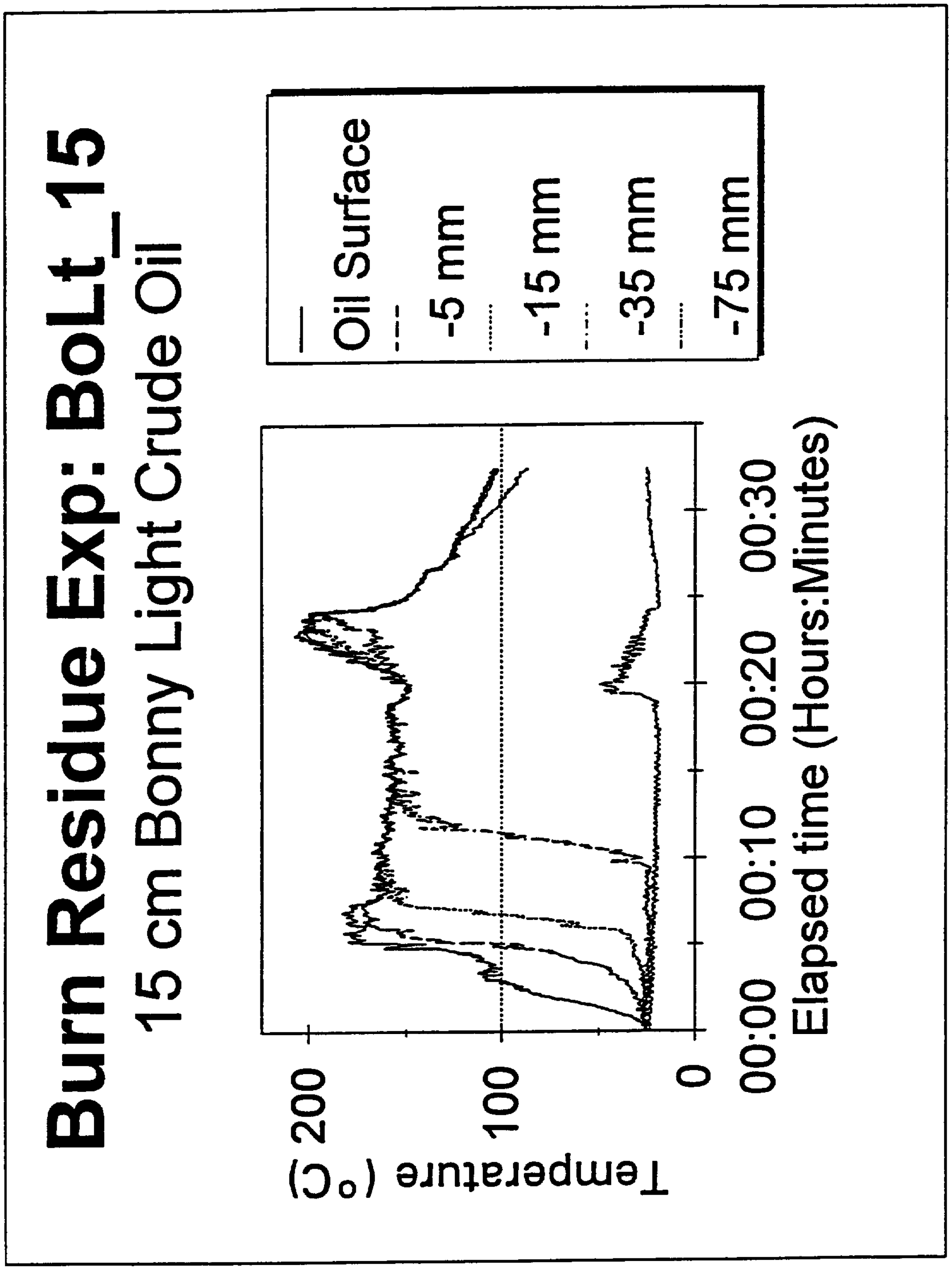
-15 mm
-35 mm
-75 mm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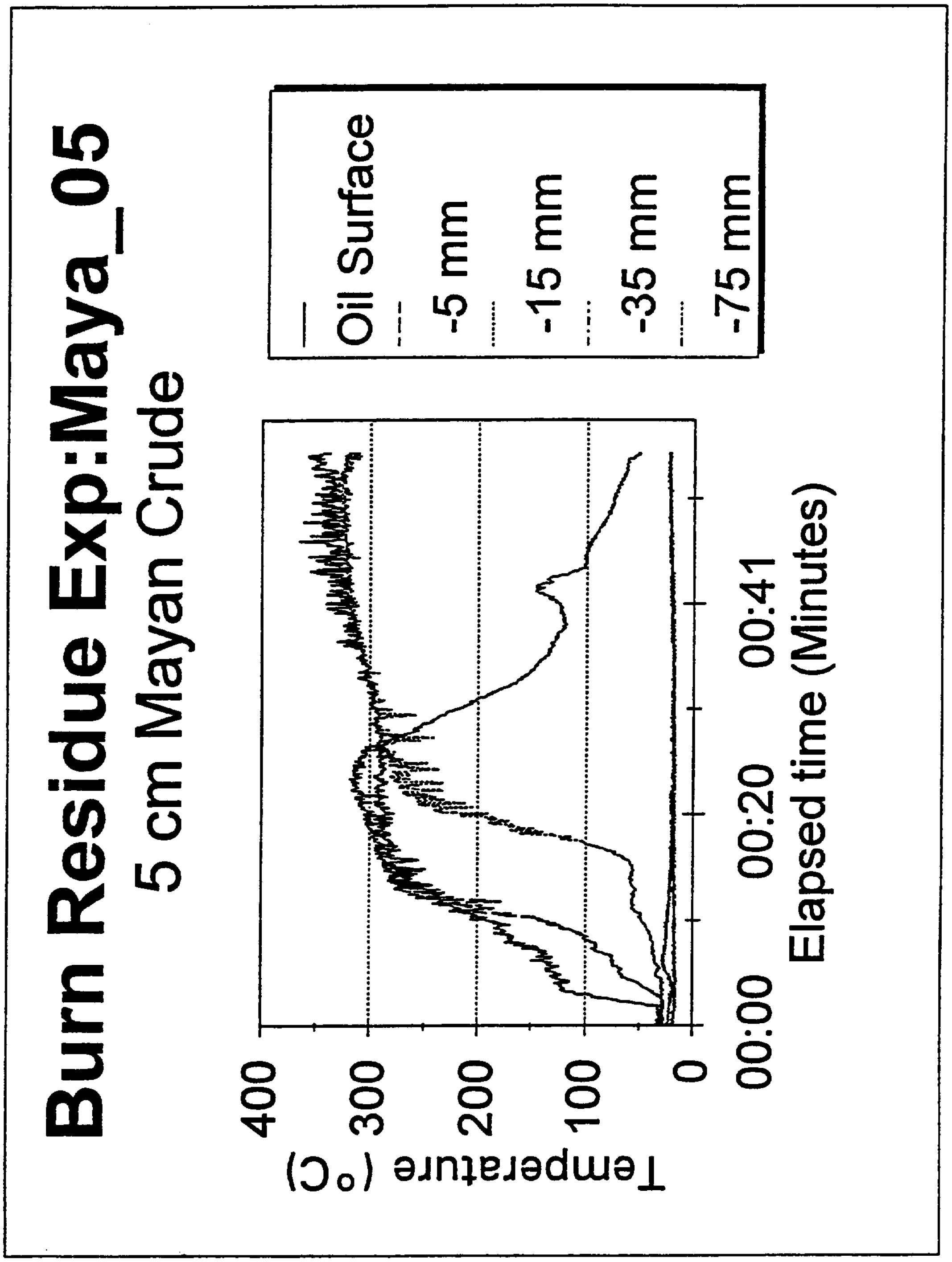
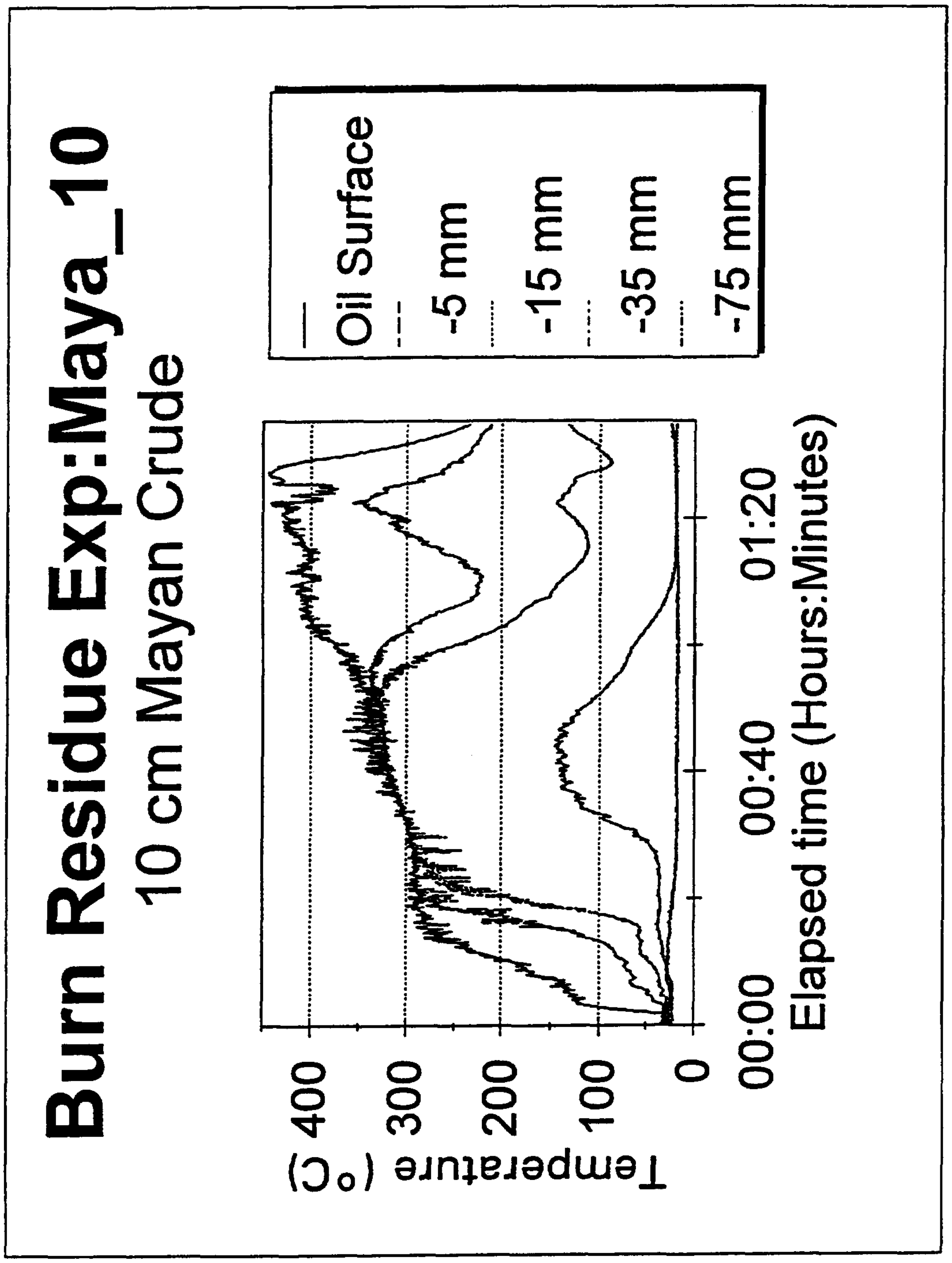
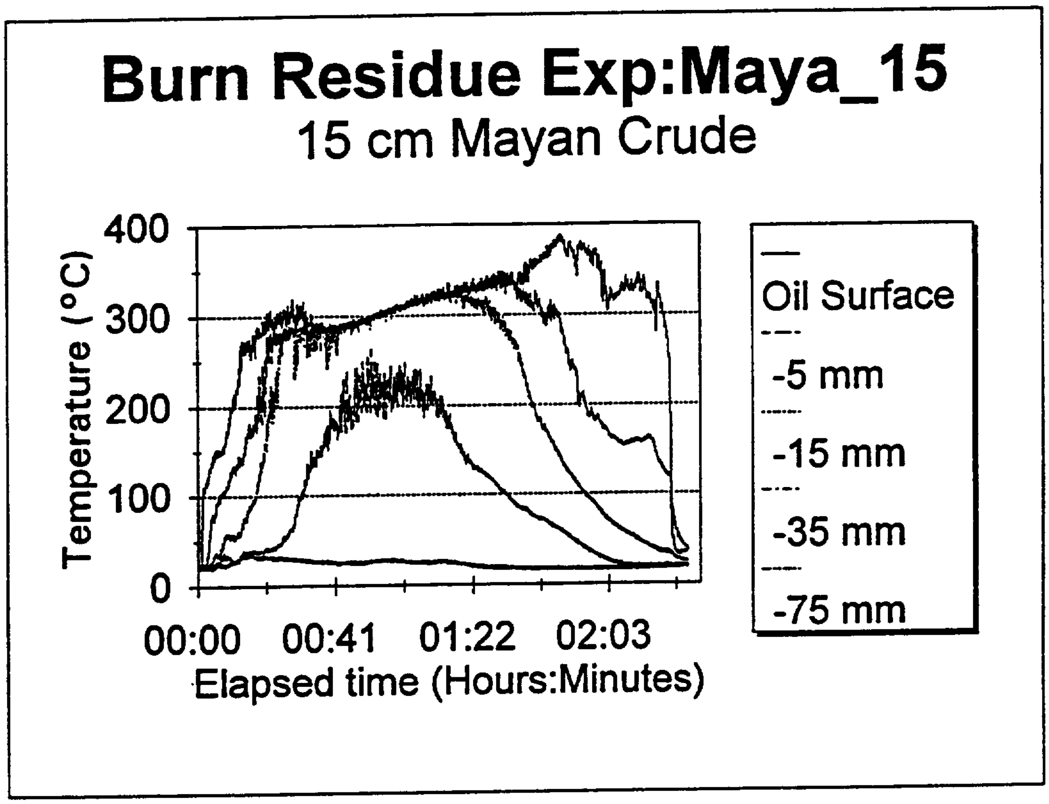
15 cm Bonny Light Crude Oil
Temperature (°C)
200
100
0
00:00
00:10
00:20
00:30
Elapsed time (Hours:Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm

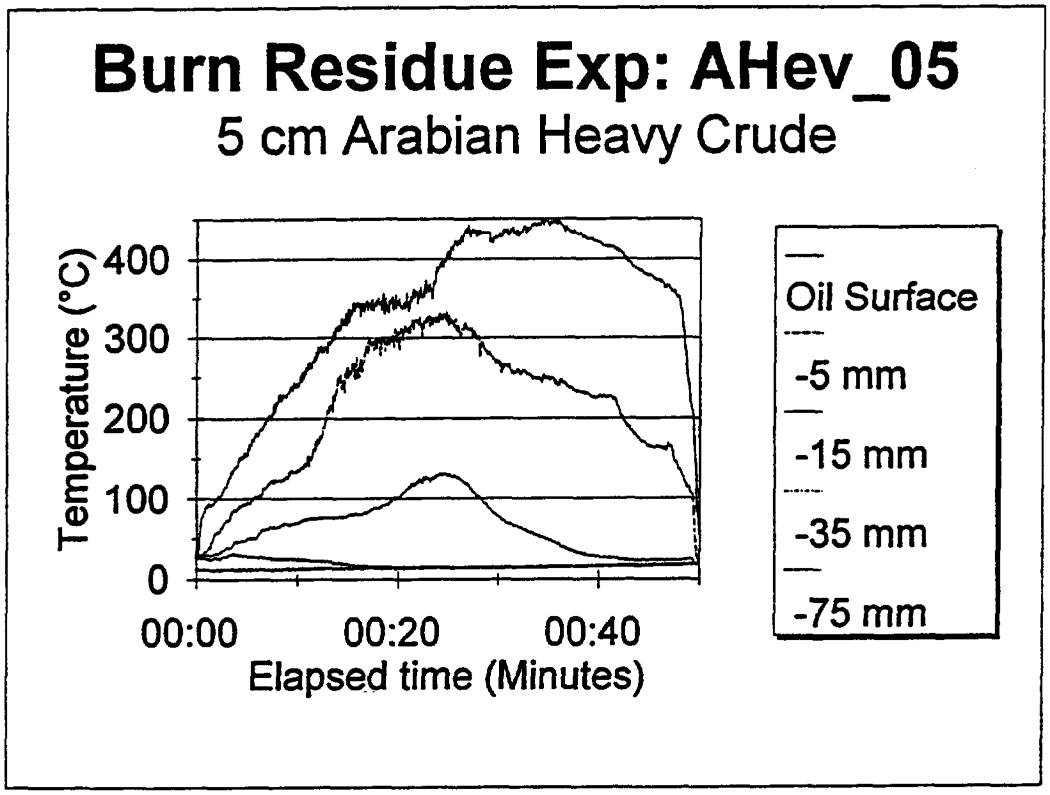

Burn Residue Exp:Maya_05
5 cm Mayan Crude
Temperature (°C)
400
300
200
100
0
00:00
00:20
00:41
Elapsed time (Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm

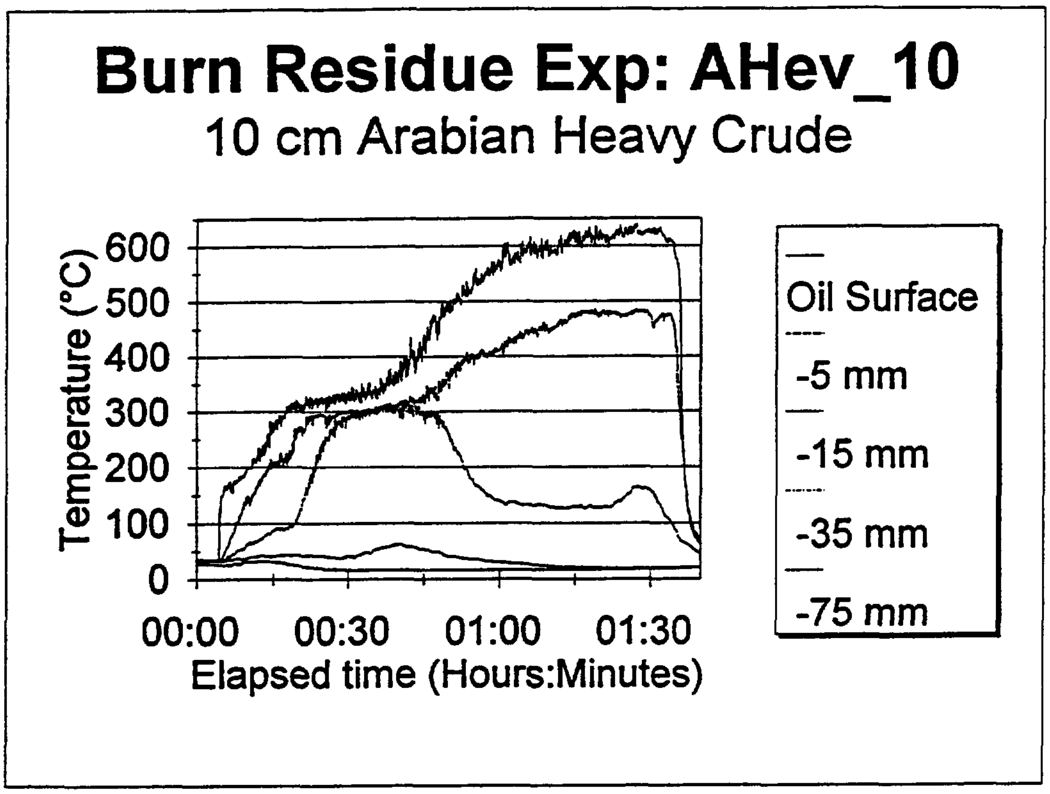


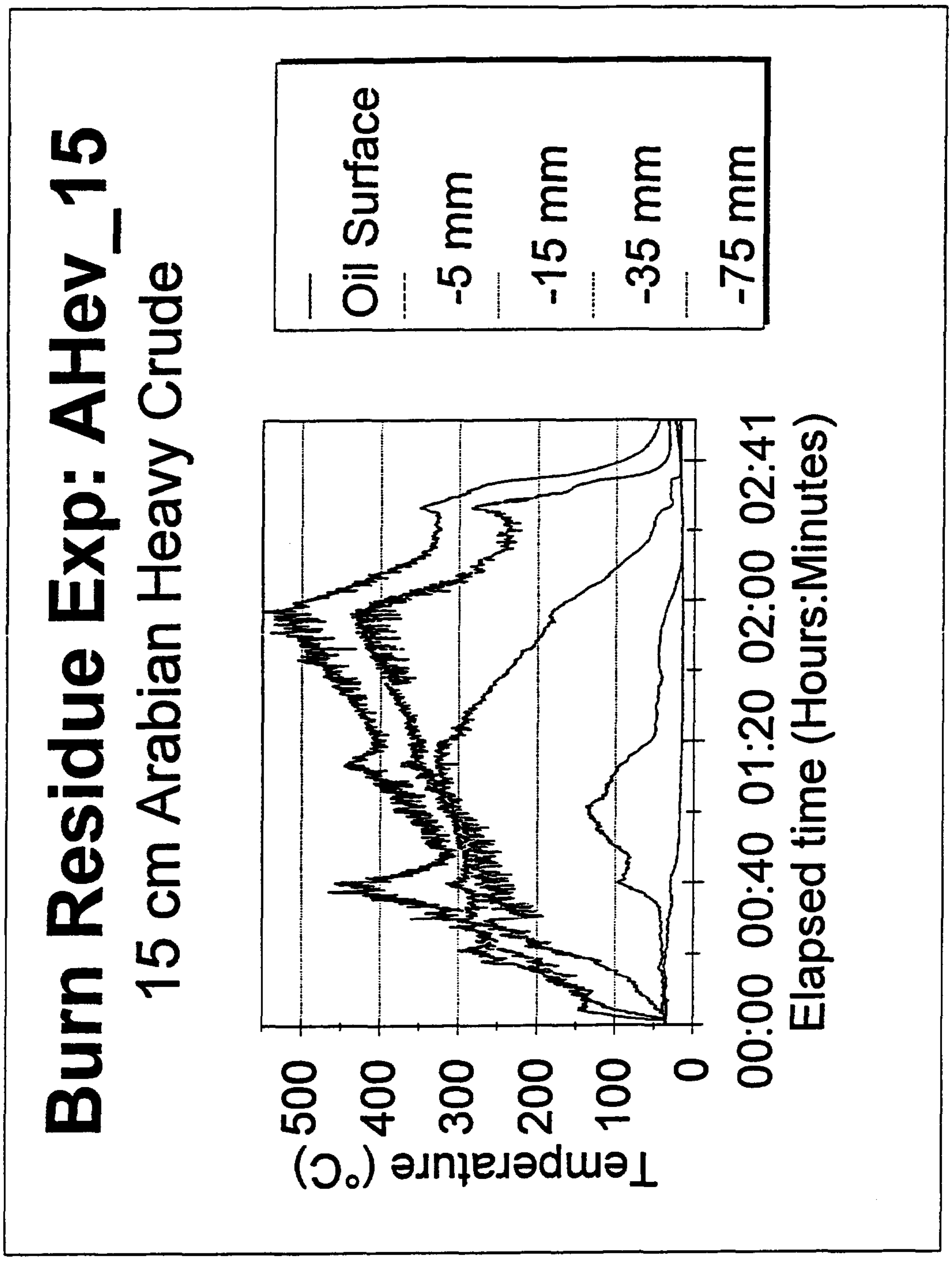
Burn Residue Exp:Maya_10
10 cm Mayan Crude
Temperature (°C)
400
300
200
100
0
00:00
00:40
01:20
Elapsed time (Hours:Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm

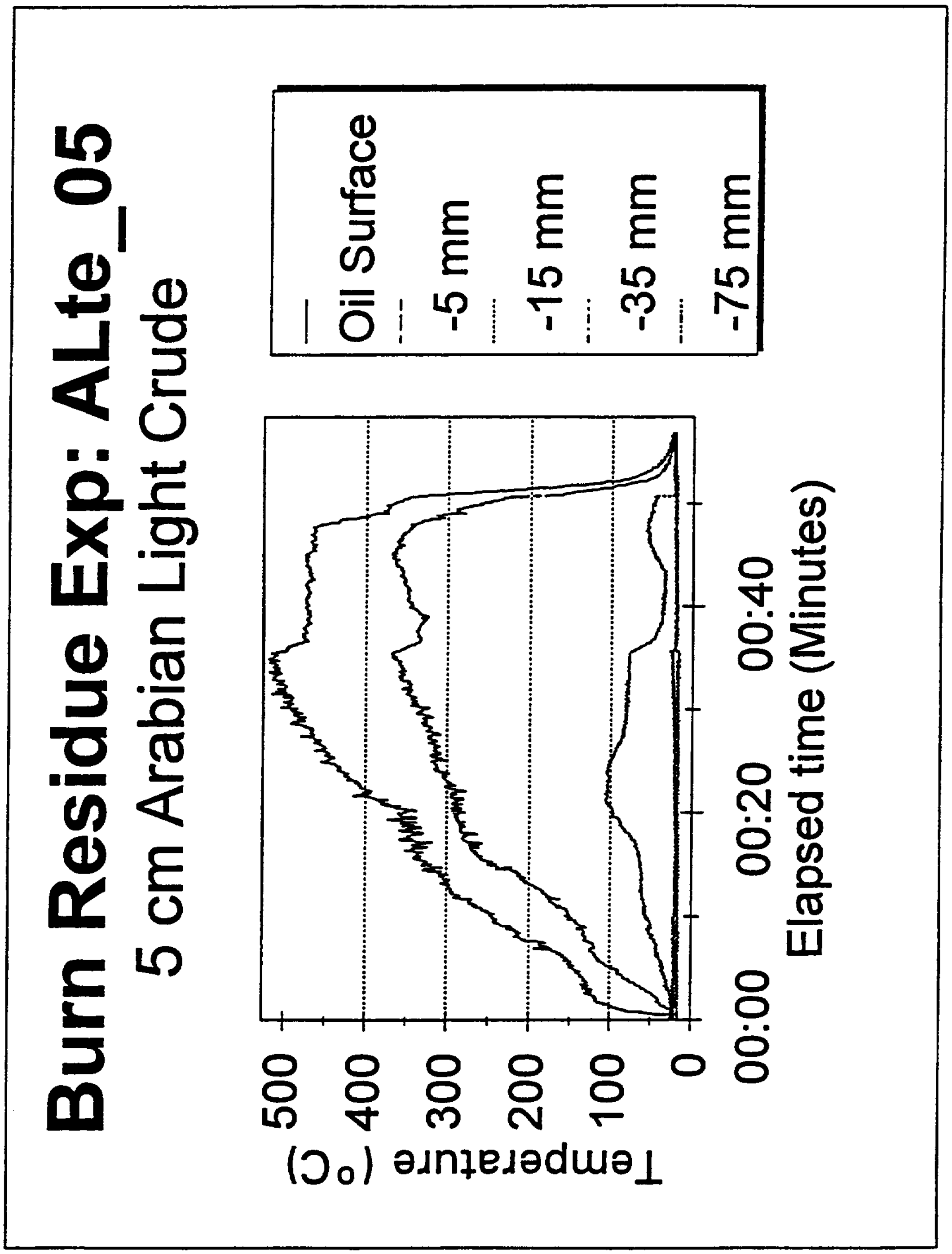


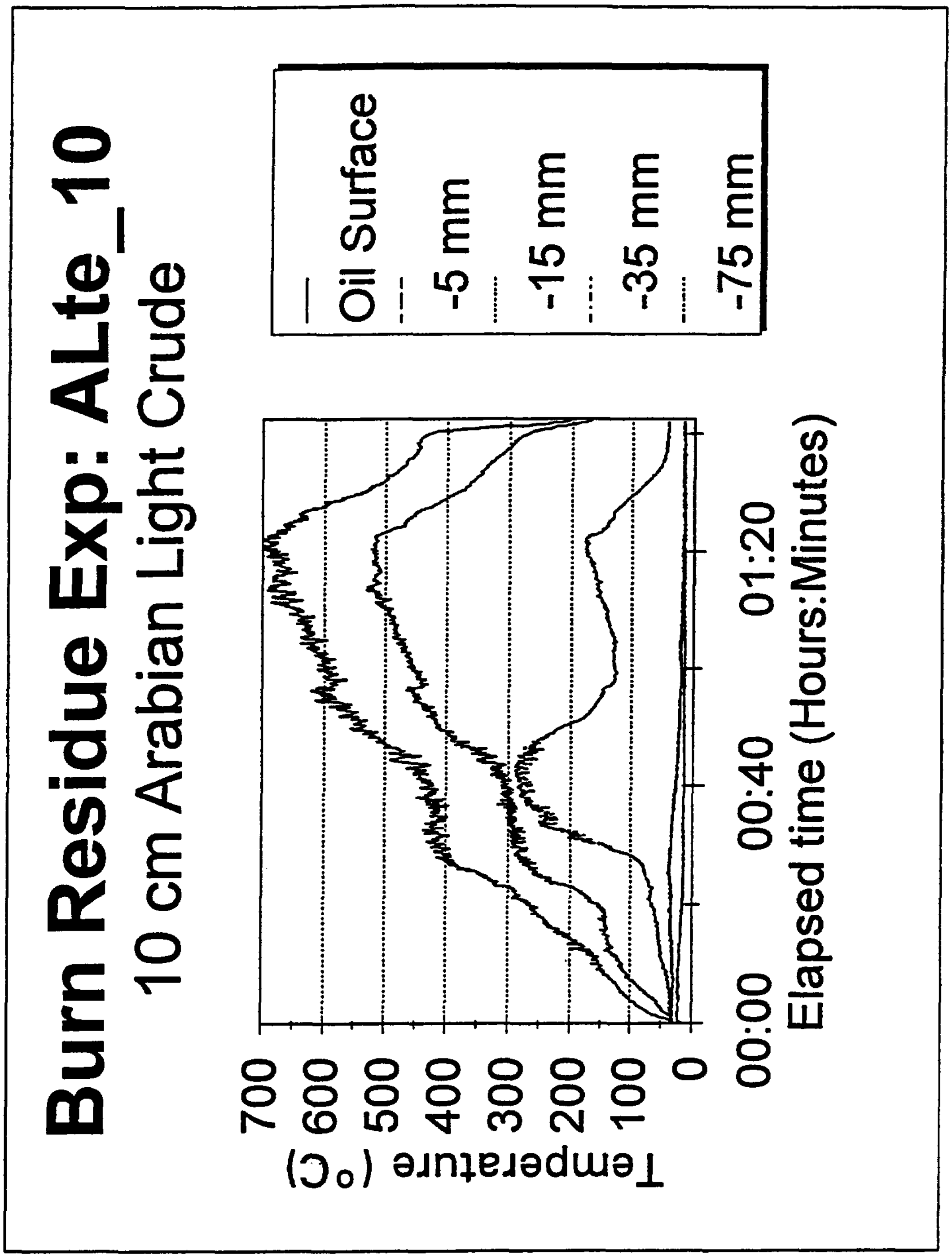
Burn Residue Exp:Maya_15
15 cm Mayan Crude
Temperature (°C)
400
300
200
100
0
00:00
00:41
01:22
02:03
Elapsed time (Hours:Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm


Burn Residue Exp: AHev_05
5 cm Arabian Heavy Crude
Temperature (°C)
400
300
200
100
0
00:00
00:20
00:40
Elapsed time (Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm

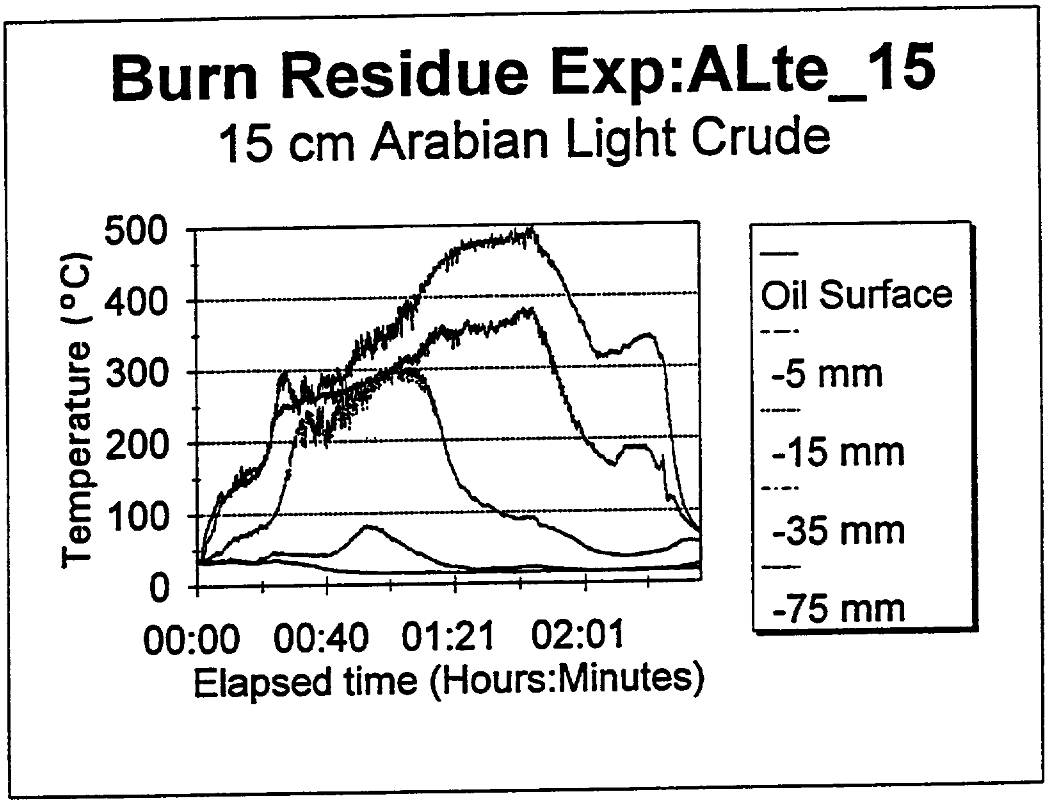

Burn Residue Exp: AHev_10
10 cm Arabian Heavy Crude
Temperature (°C)
600
500
400
300
200
100
0
00:00
00:30
01:00
01:30
Elapsed time (Hours:Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm

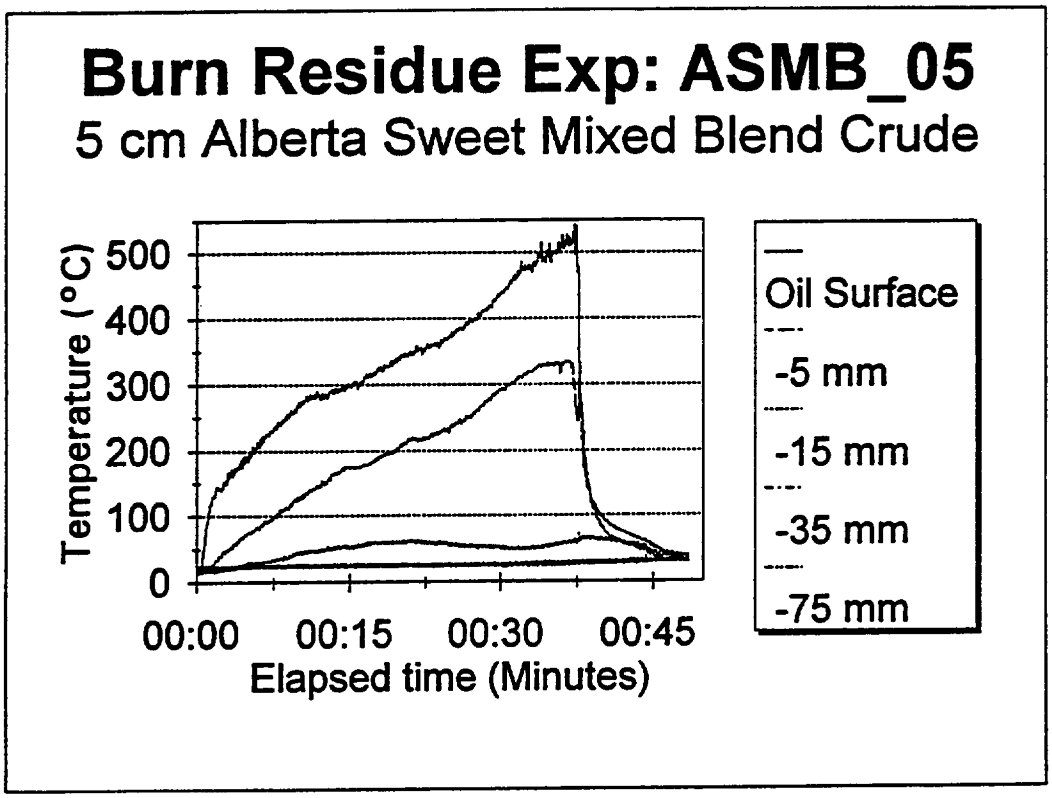

Burn Residue Exp: AHev_15
15 cm Arabian Heavy Crude
Temperature (°C)
500
400
300
200
100
0
00:00 00:40 01:20 02:00 02:41
Elapsed time (Hours:Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm

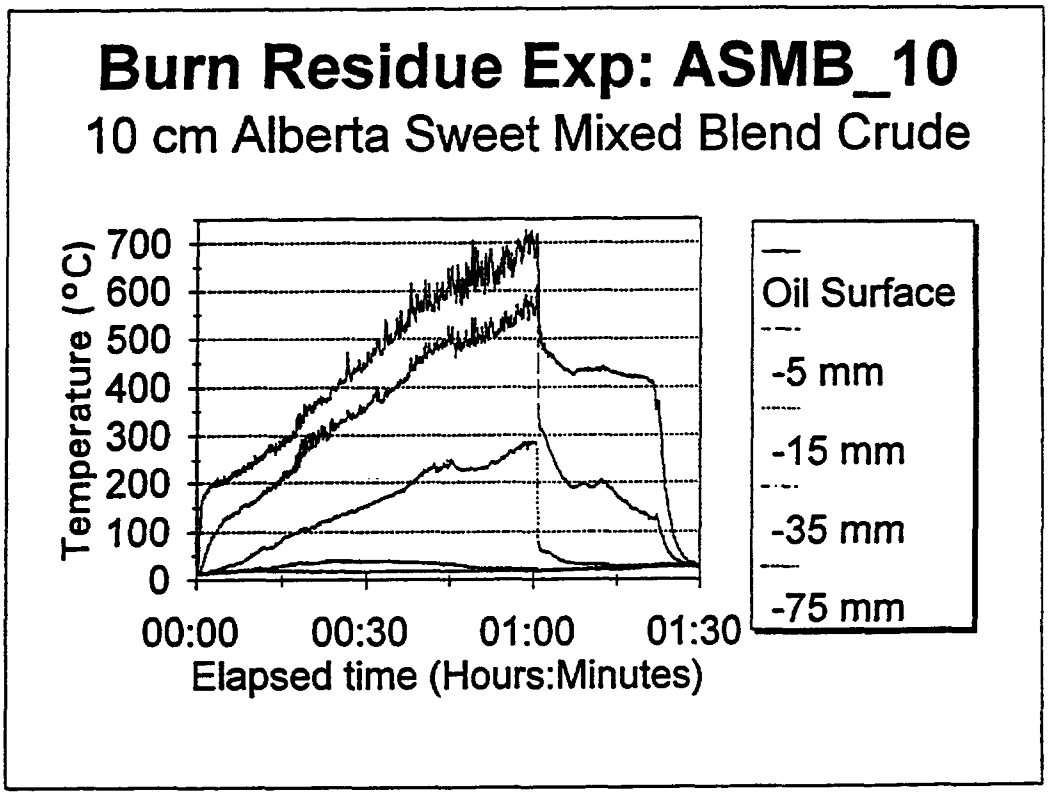

Burn Residue Exp: ALte_05
5 cm Arabian Light Crude
Temperature (°C)
500
400
300
200
100
0
00:00
00:20
00:40
Elapsed time (Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm

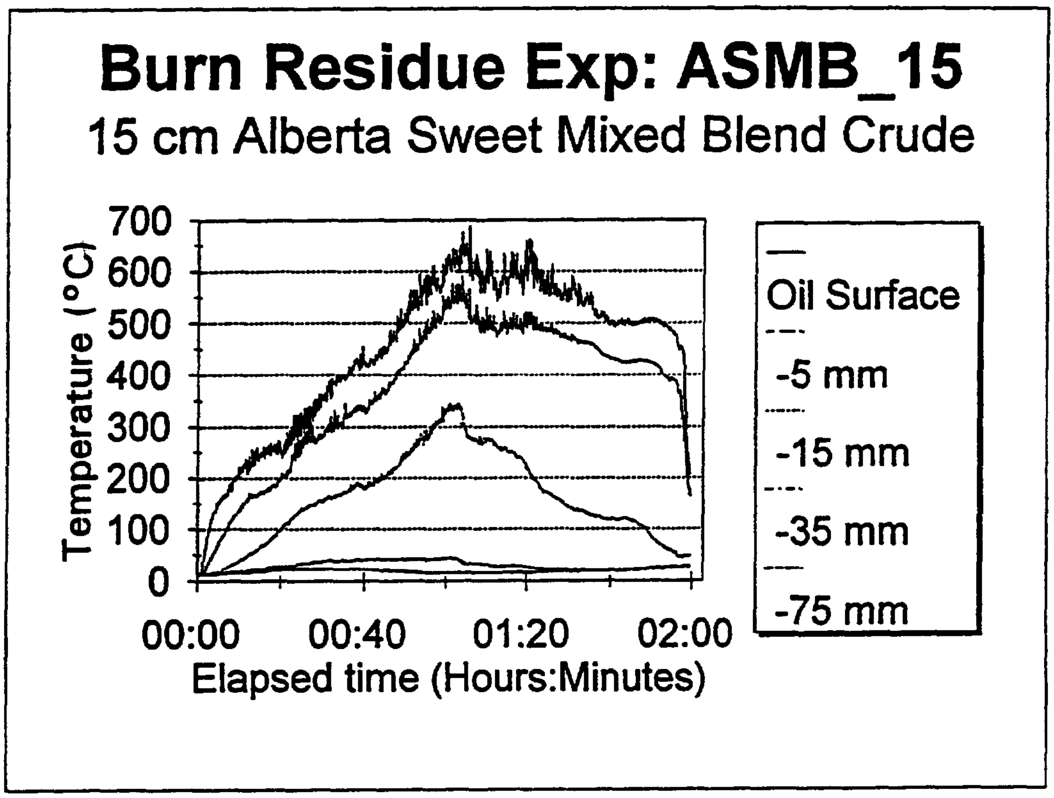


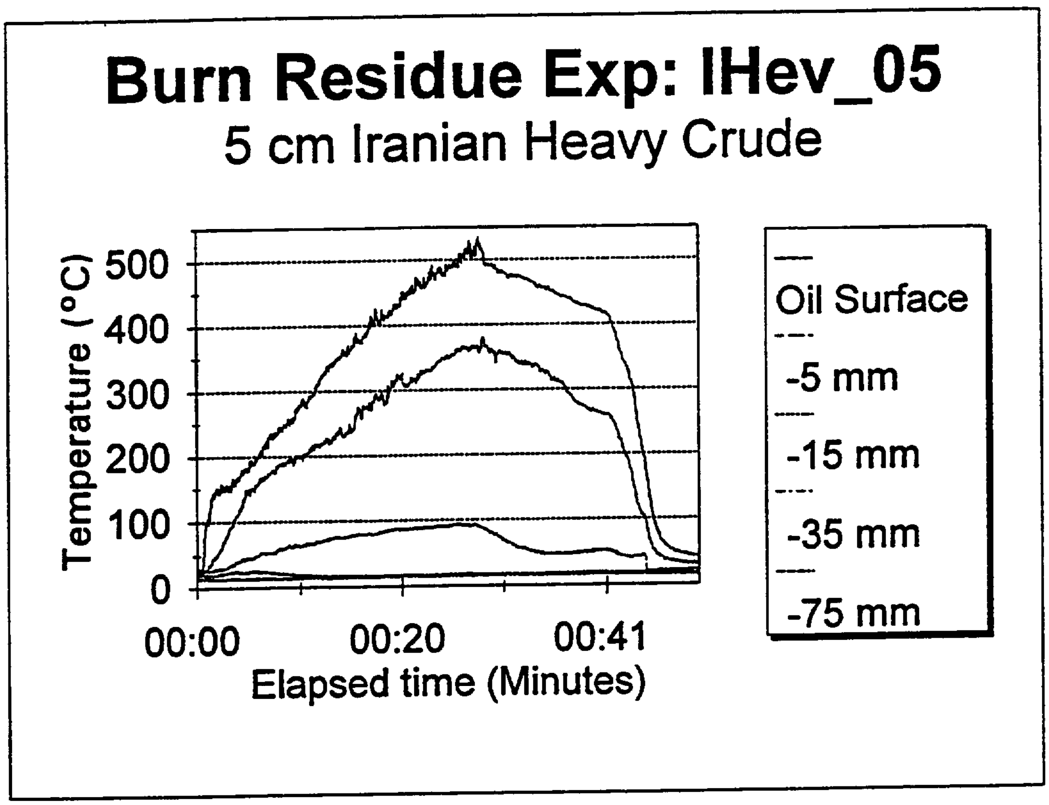
Burn Residue Exp: ALte_10
10 cm Arabian Light Crude
Temperature (°C)
700
600
500
400
300
200
100
0
00:00
00:40
01:20
Elapsed time (Hours:Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm

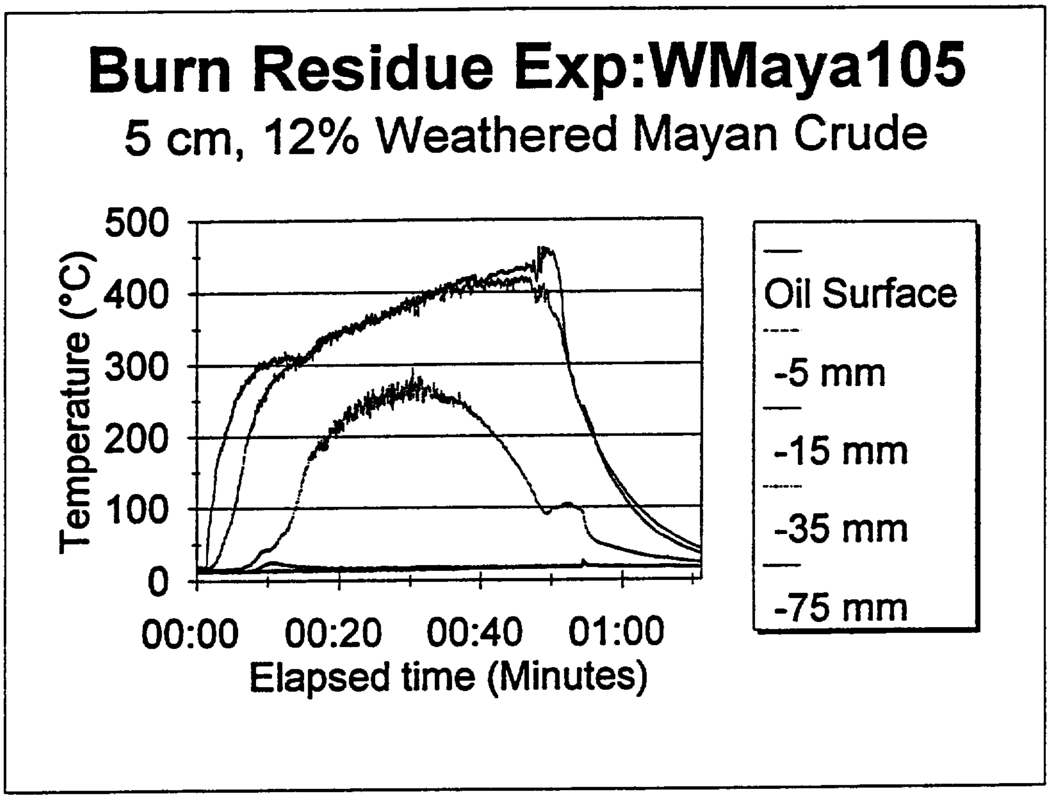

Burn Residue Exp:ALte_15
15 cm Arabian Light Crude
Temperature (°C)
500
400
300
200
100
0
00:00 00:40 01:21 02:01
Elapsed time (Hours:Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm

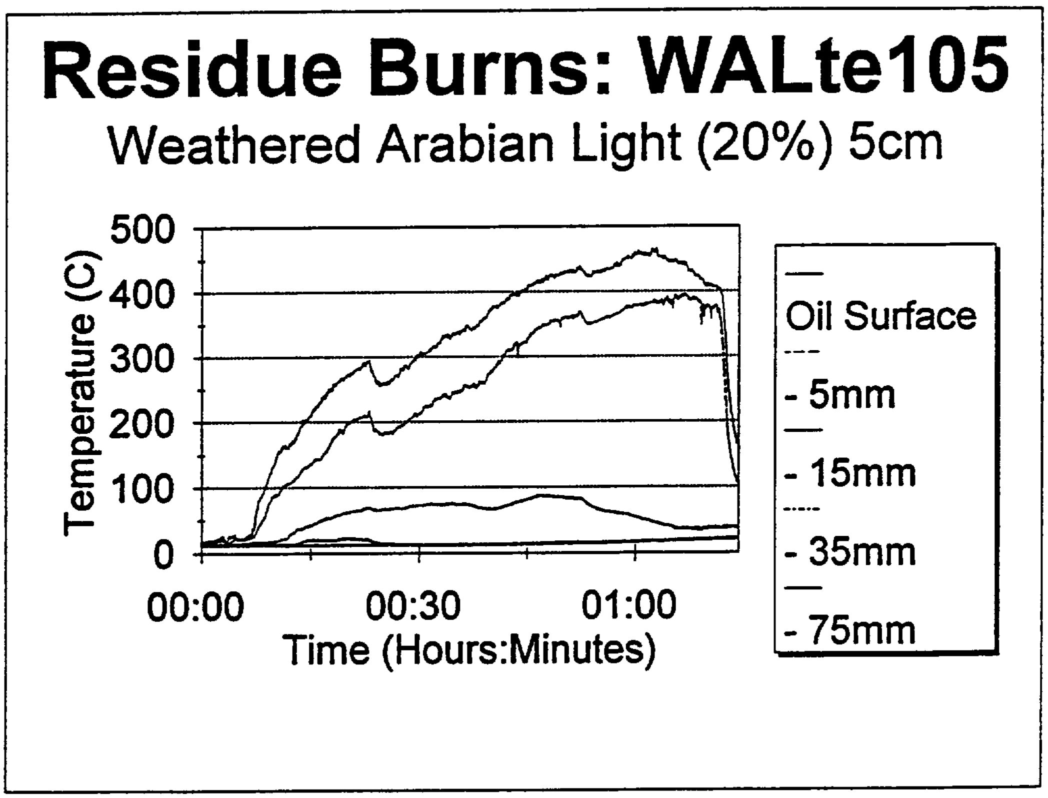

Burn Residue Exp: ASMB_05
5 cm Alberta Sweet Mixed Blend Crude
Temperature (°C)
500
400
300
200
100
0
00:00
00:15
00:30
00:45
Elapsed time (Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm

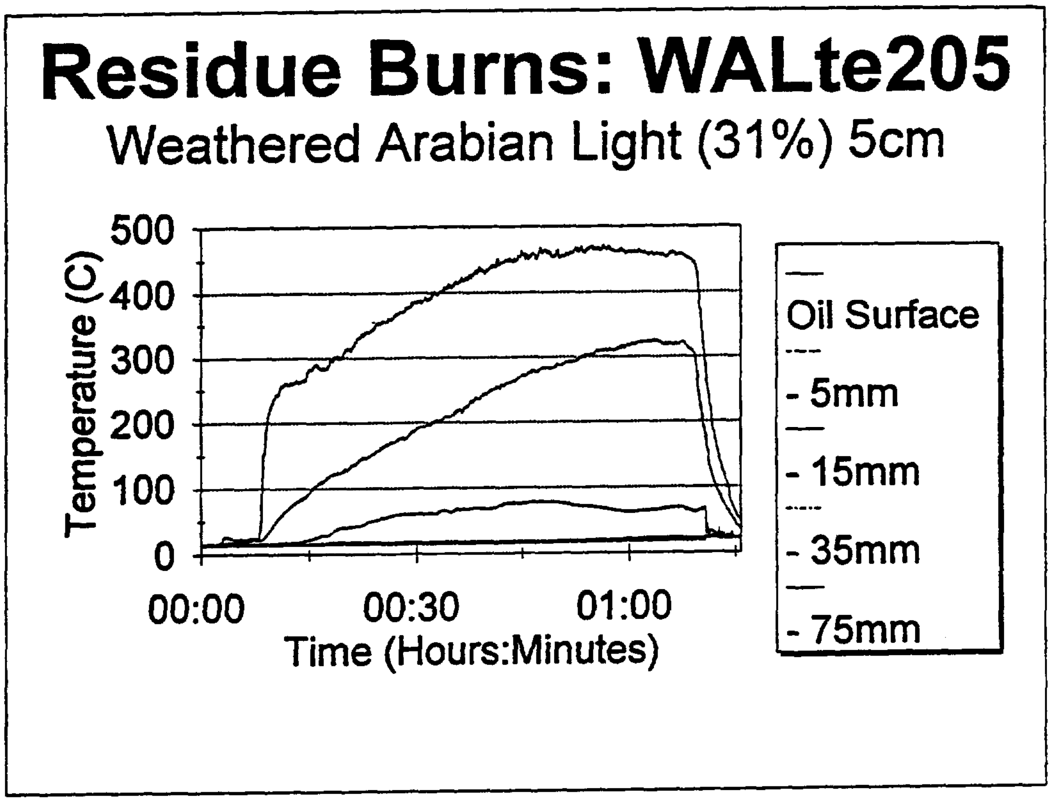

Burn Residue Exp: ASMB_10
10 cm Alberta Sweet Mixed Blend Crude
Temperature (°C)
700
600
500
400
300
200
100
0
00:00
00:30
01:00
01:30
Elapsed time (Hours:Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm

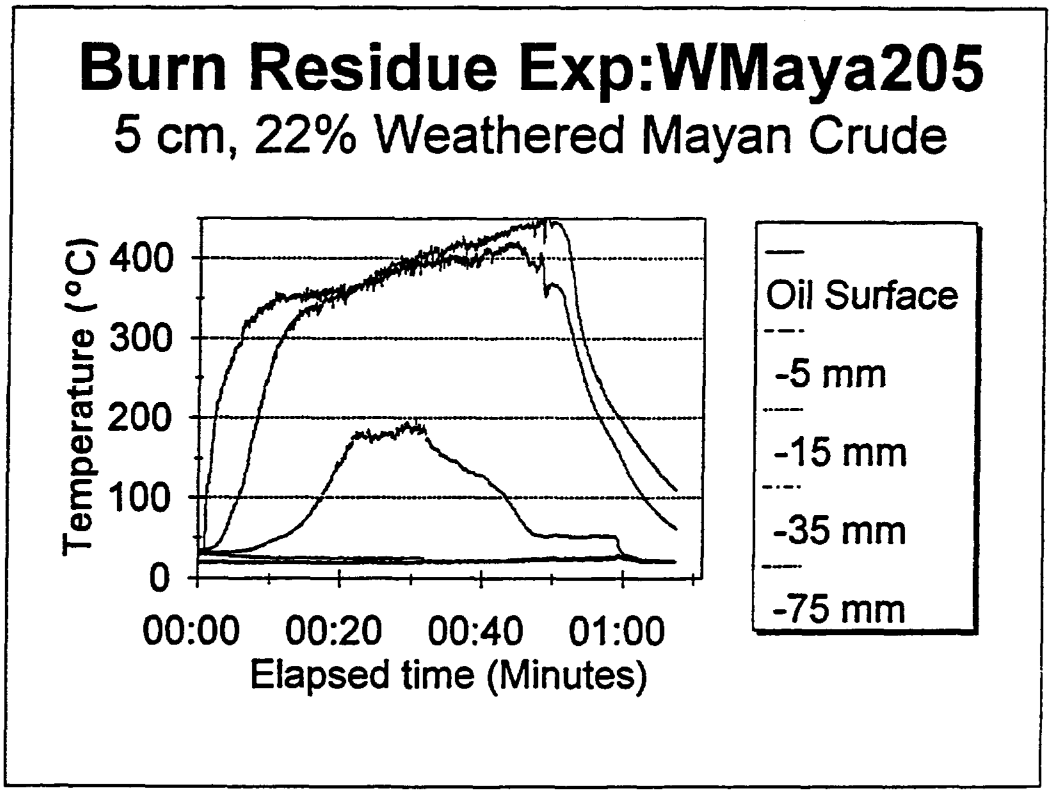

Burn Residue Exp: ASMB_15
15 cm Alberta Sweet Mixed Blend Crude
Temperature (°C)
700
600
500
400
300
200
100
0
00:00
00:40
01:20
02:00
Elapsed time (Hours:Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm


Burn Residue Exp: IHev_05
5 cm Iranian Heavy Crude
Temperature (°C)
500
400
300
200
100
0
00:00
00:20
00:41
Elapsed time (Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm


Burn Residue Exp:WMaya105
5 cm, 12% Weathered Mayan Crude
Temperature (°C)
500
400
300
200
100
0
00:00
00:20
00:40
01:00
Elapsed time (Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm


Residue Burns: WALte105
Weathered Arabian Light (20%) 5cm
500
400
300
200
100
0
Temperature (C)
00:00
00:30
01:00
Time (Hours:Minutes)
Oil Surface
- 5mm
- 15mm
- 35mm
- 75mm


Residue Burns: WALte205
Weathered Arabian Light (31%) 5cm
Temperature (C)
500
400
300
200
100
0
00:00
00:30
01:00
Time (Hours:Minutes)
Oil Surface
- 5mm
- 15mm
- 35mm
- 75mm



Burn Residue Exp:WMaya205
5 cm, 22% Weathered Mayan Crude
Temperature (°C)
400
300
200
100
0
00:00
00:20
00:40
01:00
Elapsed time (Minutes)
Oil Surface
-5 mm
-15 mm
-35 mm
-75 mm

Appendix B

CORE Laboratories Analyses Report

In-Situ Burn Residue Study
for

S.L. Ross Environmental Research

52134-95-0464
1995 06 27

A product of
Core Laboratories

Reports Distributed to: Dr. Ken Trudel - S.L. Ross Environmental, Ottawa - 2 Bound Copies and Invoice

CORE LABORATORIES

CORE Laboratories Canada Ltd.

SUMMARY OF TEST RESULTS 52134-95-464				
COMPANY.......: S. L. Ross Environmental Research Ltd. CRUDE............: Alaska North Slope SAMPLED........: March, 1995				
Comparison Of Whole Crude & Burn Residues				
	Crude	5 cm Burn	10 cm Burn	15 cm Burn
Percent Solid Wt %		8.88	4.97	21.21
Yield by ASTM D-1160 (WT %)				
IBP -400 Deg. F	17.24	0.00	0.00	0.00
400-1000 Deg. F *	57.74	9.60	6.31	8.76
1000 PLUS *	25.02	90.40	93.69	91.24
Total	100.00	100.00	100.00	100.00
* Maximium Distillation Temperature Obtained (Deg. F) by ASTM D-1160	1000	924	971	938
FIA - ASTM D-1319 (IBP-400 Deg. F)				
Saturates LV %	91.0			
Olefins LV %	0.0			
Aromatics LV %	9.0			
Total LV %	100.0			
BSG - ASTM D-2549 (400-1000 Deg. F)				
Saturates Wt %	58.26	42.54	39.35	38.69
Aromatics Wt %	38.85	53.39	56.48	56.72
Polar Aromatics Wt %	2.89	4.07	4.17	4.59
Total Wt %	100.00	100.00	100.00	100.00
SARA (1000 Deg. F PLUS)				
Saturates Wt %	14.60	8.38	7.05	7.36
Aromatics Wt %	53.10	38.83	36.54	37.87
Resins Wt %	16.77	12.69	12.18	10.90
Asphaltenes Wt %	15.53	40.10	44.23	43.87
Total Wt %	100.00	100.00	100.00	100.00
PAGE: 1				

CORE Laboratories Canada Ltd.

SUMMARY OF TEST RESULTS

52134-95-464

COMPANY.......: S. L. Ross Environmental Research Ltd.
CRUDE............: Alberta Sweet Mixed Blend
SAMPLED........: March, 1995

Comparison Of Whole Crude & Burn Residues

		Crude	5 cm Burn	10 cm Burn	15 cm Burn
Percent Solid Wt %			0.62	17.22	34.06
Yield by ASTM D-1160 (WT %)					
IBP -400 Deg. F		21.87	0.00	0.00	0.00
400-1000 Deg. F *		63.65	25.66	7.60	4.03
1000 PLUS *		14.48	74.34	92.40	95.97
Total		100.00	100.00	100.00	100.00
* Maximium Distillation Temperature Obtained (Deg. F) by ASTM D-1160		1000	1000	956	900
FIA - ASTM D-1319 (IBP-400 Deg. F)					
Saturates	LV %	86.0			
Olefins	LV %	0.8			
Aromatics	LV %	13.2			
Total	LV %	100.0			
BSG - ASTM D-2549 (400-1000 Deg. F)					
Saturates	Wt %	66.88	51.55	46.75	48.98
Aromatics	Wt %	30.58	44.44	48.46	47.36
Polar Aromatics	Wt %	2.54	4.01	4.79	3.66
Total	Wt %	100.00	100.00	100.00	100.00
SARA (1000 Deg. F PLUS)					
Saturates	Wt %	26.89	22.01	11.25	9.51
Aromatics	Wt %	47.21	49.69	38.50	35.73
Resins	Wt %	14.75	14.15	10.50	8.82
Asphaltenes	Wt %	11.15	14.15	39.75	45.94
Total	Wt %	100.00	100.00	100.00	100.00

PAGE: 2

CORE Laboratories Canada Ltd.

SUMMARY OF TEST RESULTS
52134-95-464

COMPANY.......: S. L. Ross Environmental Research Ltd.
CRUDE............: Arabian Heavy
SAMPLED........: March, 1995

Comparison Of Whole Crude & Burn Residues

		Crude	5 cm Burn	10 cm Burn	15 cm Burn
Percent Solid Wt %			9.43	0.49	13.11
Yield by ASTM D-1160 (WT %)					
IBP -400 Deg. F		15.62	0.00	0.00	0.00
400-1000 Deg. F *		49.88	9.26	8.21	8.70
1000 PLUS *		34.50	90.74	91.79	91.30
Total		100.00	100.00	100.00	100.00
* Maximium Distillation Temperature Obtained (Deg. F) by ASTM D-1160		993	943	949	974
FIA - ASTM D-1319 (IBP-400 Deg. F)					
Saturates	LV %	93.8			
Olefins	LV %	0.0			
Aromatics	LV %	6.2			
Total	LV %	100.0			
BSG - ASTM D-2549 (400-1000 Deg. F)					
Saturates	Wt %	56.22	36.40	35.92	36.03
Aromatics	Wt %	42.06	60.50	60.82	59.37
Polar Aromatics	Wt %	1.72	3.10	3.26	4.60
Total	Wt %	100.00	100.00	100.00	100.00
SARA (1000 Deg. F PLUS)					
Saturates	Wt %	10.98	6.19	6.35	8.41
Aromatics	Wt %	52.61	39.85	40.32	42.06
Resins	Wt %	11.27	8.17	12.06	10.28
Asphaltenes	Wt %	25.14	45.79	41.27	39.25
Total	Wt %	100.00	100.00	100.00	100.00

PAGE: 3

CORE Laboratories Canada Ltd.

SUMMARY OF TEST RESULTS 52134-95-464				
COMPANY.......: S. L. Ross Environmental Research Ltd. CRUDE............: Arabian Light SAMPLED........: March, 1995				
Comparison Of Whole Crude & Burn Residues				
	Crude	5 cm Burn	10 cm Burn	15 cm Burn
Percent Solid Wt %		2.57	3.89	11.99
Yield by ASTM D-1160 (WT %)				
IBP -400 Deg. F	18.55	0.00	0.00	0.00
400-1000 Deg. F *	55.37	9.25	5.26	6.50
1000 PLUS *	26.08	90.75	94.74	93.50
Total	100.00	100.00	100.00	100.00
* Maximium Distillation Temperature Obtained (Deg. F) by ASTM D-1160	1000	918	942	905
FIA - ASTM D-1319 (IBP-400 Deg. F)				
Saturates LV %	91.9			
Olefins LV %	0.0			
Aromatics LV %	8.1			
Total LV %	100.0			
BSG - ASTM D-2549 (400-1000 Deg. F)				
Saturates Wt %	56.78	36.52	38.54	36.08
Aromatics Wt %	41.14	60.64	58.53	61.20
Polar Aromatics Wt %	2.08	2.84	2.93	2.72
Total Wt %	100.00	100.00	100.00	100.00
SARA (1000 Deg. F PLUS)				
Saturates Wt %	14.29	8.78	8.40	7.44
Aromatics Wt %	54.81	48.58	45.11	43.52
Resins Wt %	13.29	11.29	9.52	8.54
Asphaltenes Wt %	17.61	31.35	36.97	40.50
Total Wt %	100.00	100.00	100.00	100.00
PAGE: 4				

CORE Laboratories Canada Ltd.

SUMMARY OF TEST RESULTS
52134-95-464

COMPANY.......: S. L. Ross Environmental Research Ltd.
CRUDE............: 20 % Weathered Arabian Light
SAMPLED........: March, 1995

Comparison Of Whole Crude & Burn Residues

		Crude	5 cm Burn		
Percent Solid Wt %			2.83		
Yield by ASTM D-1160 (WT %)					
IBP -400 Deg. F		9.07	0.00		
400-1000 Deg. F *		61.51	5.35		
1000 PLUS *		29.42	94.65		
Total		100.00	100.00		
* Maximium Distillation Temperature Obtained (Deg. F) by ASTM D-1160		1000	954.00		
FIA - ASTM D-1319 (IBP-400 Deg. F)					
Saturates	LV %	80.9			
Olefins	LV %	0.0			
Aromatics	LV %	19.1			
Total	LV %	100.0			
BSG - ASTM D-2549 (400-1000 Deg. F)					
Saturates	Wt %	56.81	39.01		
Aromatics	Wt %	40.96	57.67		
Polar Aromatics	Wt %	2.23	3.32		
Total	Wt %	100.00	100.00		
SARA (1000 Deg. F PLUS)					
Saturates	Wt %	14.29	8.08		
Aromatics	Wt %	54.40	40.39		
Resins	Wt %	12.77	10.03		
Asphaltenes	Wt %	18.54	41.50		
Total	Wt %	100.00	100.00		

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CORE Laboratories Canada Ltd.

SUMMARY OF TEST RESULTS
52134-95-464

COMPANY.......: S. L. Ross Environmental Research Ltd.
CRUDE............: 31 % Weathered Arabian Light
SAMPLED........: March, 1995

Comparison Of Whole Crude & Burn Residues

		Crude	5 cm Burn		
Percent Solid Wt %			7.87		
Yield by ASTM D-1160 (WT %)					
IBP -400 Deg. F		2.03	0.00		
400-1000 Deg. F *		64.80	8.75		
1000 PLUS *		33.17	91.25		
Total		100.00	100.00		
* Maximium Distillation Temperature Obtained (Deg. F) by ASTM D-1160		1000	889		
FIA - ASTM D-1319 (IBP-400 Deg. F)					
Saturates	LV %	80.4			
Olefins	LV %	0.0			
Aromatics	LV %	19.6			
Total	LV %	100.0			
BSG - ASTM D-2549 (400-1000 Deg. F)					
Saturates	Wt %	56.45	37.58		
Aromatics	Wt %	41.43	59.33		
Polar Aromatics	Wt %	2.12	3.09		
Total	Wt %	100.00	100.00		
SARA (1000 Deg. F PLUS)					
Saturates	Wt %	14.84	7.29		
Aromatics	Wt %	54.60	43.15		
Resins	Wt %	11.57	9.91		
Asphaltenes	Wt %	18.99	39.65		
Total	Wt %	100.00	100.00		

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CORE Laboratories Canada Ltd.

SUMMARY OF TEST RESULTS
52134-95-464

COMPANY.......: S. L. Ross Environmental Research Ltd.
CRUDE............: Bonny Light
SAMPLED........: March, 1995

Comparison Of Whole Crude & Burn Residues

		Crude	5 cm Burn	10 cm Burn	15 cm Burn
Percent Solid Wt %			0.00	0.00	0.00
Yield by ASTM D-1160 (WT %)					
IBP -400 Deg. F		20.61	0.00	0.00	28.60
400-1000 Deg. F *		71.81	41.46	14.70	59.81
1000 PLUS *		7.58	58.54	85.30	11.59
Total		100.00	100.00	100.00	100.00
* Maximium Distillation Temperature Obtained (Deg. F) by ASTM D-1160		1000	1000	988	960
FIA - ASTM D-1319 (IBP-400 Deg. F)					
Saturates	LV %	89.8			84.7
Olefins	LV %	0.0			0.0
Aromatics	LV %	10.2			15.3
Total	LV %	100.0			100.0
BSG - ASTM D-2549 (400-1000 Deg. F)					
Saturates	Wt %	67.51	48.23	45.91	65.92
Aromatics	Wt %	30.24	46.25	47.15	31.98
Polar Aromatics	Wt %	2.25	5.52	6.94	2.10
Total	Wt %	100.00	100.00	100.00	100.00
SARA (1000 Deg. F PLUS)					
Saturates	Wt %	16.88	16.51	12.85	20.67
Aromatics	Wt %	58.28	57.63	54.55	58.05
Resins	Wt %	21.66	20.56	22.26	19.64
Asphaltenes	Wt %	3.18	5.30	10.34	1.64
Total	Wt %	100.00	100.00	100.00	100.00

CORE Laboratories Canada Ltd.

SUMMARY OF TEST RESULTS
52134-95-464

COMPANY.......: S. L. Ross Environmental Research Ltd.
CRUDE............: Diesel
SAMPLED........: March, 1995

Comparison Of Whole Crude & Burn Residues

		Crude	5 cm Burn	10 cm Burn	15 cm Burn
Percent Solid Wt %			0.00	0.00	0.00
Yield by ASTM D-1160 (WT %)					
IBP -400 Deg. F		18.30	1.35 *	1.80 *	4.38 *
400-1000 Deg. F *		81.70	98.65 *	98.20 *	95.62 *
1000 PLUS *		0.00	0.00 *	0.00 *	0.00 *
Total		100.00	100.00 *	100.00 *	100.00 *
* Maximium Distillation Temperature Obtained (Deg. F) by ASTM D-1160		400 PLUS	400 PLUS	400 PLUS	400 PLUS
FIA - ASTM D-1319 (IBP-400 Deg. F)					
Saturates	LV %	81.2	**	**	**
Olefins	LV %	0.5	**	**	**
Aromatics	LV %	18.3	**	**	**
Total	LV %	100.0			
BSG - ASTM D-2549 (400-1000 Deg. F)					
Saturates	Wt %	70.41	64.09 **	63.30 **	62.17 **
Aromatics	Wt %	29.04	34.70 **	35.17 **	36.21 **
Polar Aromatics	Wt %	0.55	1.21 **	1.53 **	1.62 **
Total	Wt %	100.00	100.00 **	100.00 **	100.00 **

* See Simulated Distillation Data On Pages 13, 14 & 15
** See Note On Page 16

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CORE Laboratories Canada Ltd.

SUMMARY OF TEST RESULTS
52134-95-464

COMPANY.......: S. L. Ross Environmental Research Ltd.
CRUDE............: Iranian Heavy
SAMPLED........: March, 1995

Comparison Of Whole Crude & Burn Residues

		Crude	5 cm Burn		
Percent Solid Wt %			4.21		
Yield by ASTM D-1160 (WT %)					
IBP -400 Deg. F		20.86	0.00		
400-1000 Deg. F *		52.21	13.08		
1000 PLUS *		26.93	86.92		
Total		100.00	100.00		
* Maximium Distillation Temperature Obtained (Deg. F) by ASTM D-1160		1000	973		
FIA - ASTM D-1319 (IBP-400 Deg. F)					
Saturates	LV %	92.2			
Olefins	LV %	0.0			
Aromatics	LV %	7.8			
Total	LV %	100.0			
BSG - ASTM D-2549 (400-1000 Deg. F)					
Saturates	Wt %	59.01	37.10		
Aromatics	Wt %	38.40	57.89		
Polar Aromatics	Wt %	2.59	5.01		
Total	Wt %	100.00	100.00		
SARA (1000 Deg. F PLUS)					
Saturates	Wt %	13.78	8.87		
Aromatics	Wt %	51.60	43.26		
Resins	Wt %	16.67	15.25		
Asphaltenes	Wt %	17.95	32.62		
Total	Wt %	100.00	100.00		

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CORE Laboratories Canada Ltd.

SUMMARY OF TEST RESULTS

52134-95-464

COMPANY.......: S. L. Ross Environmental Research Ltd.
CRUDE............: Mayan
SAMPLED........: March, 1995

Comparison Of Whole Crude & Burn Residues

		Crude	5 cm Burn	10 cm Burn	15 cm Burn
Percent Solid Wt %			12.75	4.76	8.09
Yield by ASTM D-1160 (WT %)					
IBP -400 Deg. F		14.23	0.00	0.00	0.00
400-1000 Deg. F *		45.58	9.02	14.15	13.07
1000 PLUS *		40.19	90.98	85.85	86.93
Total		100.00	100.00	100.00	100.00
* Maximium Distillation Temperature Obtained (Deg. F) by ASTM D-1160		985	907	957	960
FIA - ASTM D-1319 (IBP-400 Deg. F)					
Saturates	LV %	91.9			
Olefins	LV %	0.0			
Aromatics	LV %	8.1			
Total	LV %	100.0			
BSG - ASTM D-2549 (400-1000 Deg. F)					
Saturates	Wt %	51.31	34.48	34.47	33.48
Aromatics	Wt %	46.24	60.99	61.00	61.51
Polar Aromatics	Wt %	2.45	4.53	4.53	5.01
Total	Wt %	100.00	100.00	100.00	100.00
SARA (1000 Deg. F PLUS)					
Saturates	Wt %	6.84	5.36	5.39	5.23
Aromatics	Wt %	44.44	34.23	34.43	32.40
Resins	Wt %	13.39	9.82	12.87	11.15
Asphaltenes	Wt %	35.33	50.59	47.31	51.22
Total	Wt %	100.00	100.00	100.00	100.00

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CORE Laboratories Canada Ltd.

SUMMARY OF TEST RESULTS
52134-95-464

COMPANY.......: S. L. Ross Environmental Research Ltd.
CRUDE............: 12 % Weathered Mayan
SAMPLED........: March, 1995

Comparison Of Whole Crude & Burn Residues

		Crude	5 cm Burn		
Percent Solid Wt %			3.43		
Yield by ASTM D-1160 (WT %)					
IBP -400 Deg. F		7.37	0.00		
400-1000 Deg. F *		49.29	6.47		
1000 PLUS *		43.34	93.53		
Total		100.00	100.00		
* Maximium Distillation Temperature Obtained (Deg. F) by ASTM D-1160		1000	873		
FIA - ASTM D-1319 (IBP-400 Deg. F)					
Saturates	LV %	83.5			
Olefins	LV %	0.0			
Aromatics	LV %	16.5			
Total	LV %	100.0			
BSG - ASTM D-2549 (400-1000 Deg. F)					
Saturates	Wt %	50.67	32.85		
Aromatics	Wt %	46.29	63.64		
Polar Aromatics	Wt %	3.04	3.51		
Total	Wt %	100.00	100.00		
SARA (1000 Deg. F PLUS)					
Saturates	Wt %	6.91	4.49		
Aromatics	Wt %	41.82	30.92		
Resins	Wt %	15.27	12.97		
Asphaltenes	Wt %	36.00	51.62		
Total	Wt %	100.00	100.00		

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CORE Laboratories Canada Ltd.

SUMMARY OF TEST RESULTS 52134-95-464				
COMPANY.......: S. L. Ross Environmental Research Ltd. CRUDE............: 22 % Weathered Mayan SAMPLED........: March, 1995				
Comparison Of Whole Crude & Burn Residues				
	Crude	5 cm Burn		
Percent Solid Wt %		9.00		
Yield by ASTM D-1160 (WT %)				
IBP -400 Deg. F	0.00	0.00		
400-1000 Deg. F *	50.23	3.19		
1000 PLUS *	49.77	96.81		
Total	100.00	100.00		
* Maximium Distillation Temperature Obtained (Deg. F) by ASTM D-1160	997	774		
BSG - ASTM D-2549 (400-1000 Deg. F)				
Saturates Wt %	51.51	43.60		
Aromatics Wt %	45.59	54.51		
Polar Aromatics Wt %	2.90	1.89		
Total Wt %	100.00	100.00		
SARA (1000 Deg. F PLUS)				
Saturates Wt %	7.05	4.73		
Aromatics Wt %	43.08	29.59		
Resins Wt %	12.09	8.28		
Asphaltenes Wt %	37.78	57.40		
Total Wt %	100.00	100.00		
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CORE Laboratories Canada Ltd.

LABORATORY TEST RESULTS
6/26/95

JOB NUMBER: 52134-95-464 CUSTOMER: S.L. ROSS ENVIRONMENTAL RESEARCH LTD. ATTN: DR. KEN TRUDEL

CLIENT I.D....................: Diesel Burn Residues
DATE SAMPLED............: March 1995
TIME SAMPLED.............:
WORK DESCRIPTION.....: 5 cm Burn

LABORATORY I.D.....: 52134-95-464-1
DATE RECEIVED.......: 04/07/95
TIME RECEIVED........: 10:00 Hours
REMARKS................:

TEST DESCRIPTION	FINAL RESULT	DETECTION LIMIT	UNITS OF MEASURE	TEST METHOD	DATE	TECHN
Simulated Distillation			Deg. F	ASTM D-2887	06/09/95	RH
I.B.P.	239					
1% Off	383					
2% Off	432					
3% Off	452					
4% Off	472					
5% Off	482					
10% Off	516					
15% Off	536					
20% Off	551					
25% Off	568					
30% Off	578					
35% Off	591					
40% Off	603					
45% Off	612					
50% Off	623					
55% Off	630					
60% Off	641					
65% Off	652					
70% Off	659					
75% Off	671					
80% Off	681					
85% Off	696					
90% Off	713					
95% Off	740					
F.B.P.	862					

1540 - 25th AVE. N.E.
CALGARY, ALBERTA T2E 7R2
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CORE Laboratories Canada Ltd.

LABORATORY TEST RESULTS
6/26/95

JOB NUMBER: 52134-95-464 CUSTOMER: S.L. ROSS ENVIRONMENTAL RESEARCH LTD. ATTN: DR. KEN TRUDEL

CLIENT I.D....................: Diesel Burn Residues
DATE SAMPLED............: March 1995
TIME SAMPLED.............:
WORK DESCRIPTION.....: 10 cm Burn

LABORATORY I.D.....: 52134-95-464-2
DATE RECEIVED.......: 04/07/95
TIME RECEIVED........: 10:00 Hours
REMARKS................:

TEST DESCRIPTION	FINAL RESULT	DETECTION LIMIT	UNITS OF MEASURE	TEST METHOD	DATE	TECHN
Simulated Distillation			Deg. F	ASTM D-2887	06/09/95	RH
I.B.P.	231					
1% Off	257					
2% Off	436					
3% Off	463					
4% Off	480					
5% Off	489					
10% Off	527					
15% Off	546					
20% Off	567					
25% Off	580					
30% Off	596					
35% Off	607					
40% Off	620					
45% Off	629					
50% Off	639					
55% Off	651					
60% Off	658					
65% Off	668					
70% Off	677					
75% Off	688					
80% Off	699					
85% Off	714					
90% Off	733					
95% Off	763					
F.B.P.	886					

1540 - 25th AVE. N.E.
CALGARY, ALBERTA T2E 7R2
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CORE Laboratories Canada Ltd.

LABORATORY TEST RESULTS
6/26/95

JOB NUMBER: 52134-95-464 CUSTOMER: S.L. ROSS ENVIRONMENTAL RESEARCH LTD. ATTN: DR. KEN TRUDEL

CLIENT I.D....................: Diesel Burn Residues
DATE SAMPLED............: March 1995
TIME SAMPLED.............:
WORK DESCRIPTION.....: 15 cm Burn

LABORATORY I.D.....: 52134-95-464-3
DATE RECEIVED.......: 04/07/95
TIME RECEIVED........: 10:00 Hours
REMARKS................:

TEST DESCRIPTION	FINAL RESULT	DETECTION LIMIT	UNITS OF MEASURE	TEST METHOD	DATE	TECHN
Simulated Distillation			Deg. F	ASTM D-2887	06/09/95	RH
I.B.P.	231					
1% Off	231					
2% Off	232					
3% Off	233					
4% Off	380					
5% Off	433					
10% Off	500					
15% Off	528					
20% Off	546					
25% Off	566					
30% Off	578					
35% Off	594					
40% Off	606					
45% Off	619					
50% Off	629					
55% Off	640					
60% Off	652					
65% Off	659					
70% Off	671					
75% Off	682					
80% Off	695					
85% Off	710					
90% Off	730					
95% Off	764					
F.B.P.	889					

1540 - 25th AVE. N.E.
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CORE Laboratories Canada Ltd.

SUMMARY OF TEST RESULTS
52134-95-464

COMPANY.......: S. L. Ross Environmental Research Ltd.
CRUDE............: Burn Residues
SAMPLED........: March, 1995

Summary I.B.P. Of Burn Residues

		5 cm Burn	10 cm Burn	15 cm Burn	
Alaska North Slope	°F	563	x	590	
Alberta Sweet Mixed Blend	°F	697	720	627	
Arabian Heavy	°F	652	617	617 *	
Arabian Light	°F	580	613	633	
20 % Weathered Arabian Light	°F	x			
31 % Weathered Arabian Light	°F	x			
Bonny Light	°F	550	585		
Iranian Heavy	°F	x			
Mayan	°F	649	649	577	
12.8 % Weathered Mayan	°F	543			
22 % Weathered Mayan	°F	608			

Note:
X = I.B.P. is not recorded.
* = Sample was analysed by simulated distillation before work was done and the I.B.P was 617 deg. F.

CORE Laboratories Canada Ltd.

SUMMARY OF TEST DATA

Removal of Solids from the Burn Residues

All of the burn residues with the exception of the Diesel samples and the Bonny Light (15 cm burn residue) were heated to 325 F for two hours and filtered through a 10 mesh screen to remove the solids. The solids in each sample were measured and reported as a percent of the total sample and the ASTM D-1160 distillation and characterization of each fraction was performed on the solids free samples.

Diesel Burn Residues

The Diesel Burn residues contained a low percentage of the IBP-400 F fraction which presented difficulties in obtaining a cut of this fraction by the ASTM D-1160 Distillation. Several attempts were made to obtain this fraction, however the samples exhibited a high degree of foaming in the boiling flask, making it impossible to obtain this desired cut. Therefore the burn resides were analyzed by simulated distillation (ASTM D-2887) to quantify the IBP-400 F fraction and are reported on pages 13, 14 and 15 of this report. Since the IBP-400 F fraction could not be practically obtained for these samples the saturate / aromatic content by BSG - ASTM D-2549 was run on the burn residues as received.