

LABORATORY STUDIES OF THE PROPERTIES OF IN-SITU BURN RESIDUES: CHEMICAL COMPOSITION OF RESIDUES

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ABSTRACT

This study investigated the changes in chemical composition undergone by oils during the in-situ burning of thick slicks. It involved small-scale burns of oil pools on water, collecting samples after the natural extinction of the fire and analysing the chemical composition of the fresh oil and burn residue. Test burns were conducted on a range of oil types including seven crude oils and automotive diesel. For each oil type, slicks of fresh oil of three different thicknesses were tested. For two of the oils, tests were conducted on both fresh and weathered oil. The chemical characterization of both unburned oils and burn residues involved fractionating oil samples into boiling ranges IBP to 204°C (lower boiling point fraction, LBPF), 205°C to 538°C (middle boiling point fraction, MBPF), and greater than 538°C (higher boiling point fraction, HBPF) using the ASTM D-1160 distillation method. Each distillation fraction was further characterized by measuring each of total saturates, total aromatics, total resins, and total asphaltene using a variety of ASTM standard methods.

In all the crude oil tests, the composition of the burn residue differed very markedly from the parent oil. Burn residues were composed almost exclusively of the HBPF; virtually all of the LBPF and most of the MBPF had been removed during burning. By comparison little of the mass of the HBPF had been consumed during burning. This contrasts somewhat with the situation for automotive diesel in which a small proportion of the LBPF remained in the burn residue, although the ratio of LBPF to MBPF in the residue was much reduced over the fresh diesel. These results suggest that the in-situ burning of thick oil slicks is neither a pure "batch distillation" process nor an "equilibrium flash vaporization" process, but rather a process lying somewhere between the two ideals. Hence residues from burning thick slicks of crude oils can be expected to differ greatly in chemical composition and physical properties from the parent oil.

Results from these tests reported in previous publications showed that both density and rheology of burn residues differed among crude oils and that many of the residues were more dense than seawater and hence would sink. The results of the chemical analysis demonstrated that both density and rheology of residue were strongly correlated to the asphaltene, resin and HBP aromatic content of the oil and its residue.

From an environmental perspective, these results strongly suggest that burning thick slicks selectively removes most if not all of the lower-molecular weight aromatic hydrocarbons which include the more toxic and more bioavailable components of the crude oils. To date no attempt has been made to assess the fate of the hazardous, higher-molecular weight polynuclear aromatic hydrocarbons in these burns.

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INTRODUCTION

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 melt-pool-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. 1995a) have shown that burn residues can indeed sink.

A recent study of residues from small-scale pool-type burns of thick slicks of a variety of oils have shown that residues from efficient burns of thick slicks of heavier crudes can sink in fresh or salt water (Buist et al. 1995b, Buist and Trudel, in press). The present paper reports results of chemical analysis of the parent oils and burn residues from these studies. The data concerning burn efficiency and physical properties of the burn residues reported earlier showed the following:

- i) Residues from burns of thicker slicks of heavier oils can sink, even in marine waters.
- ii) In general, burns of heavier crude oils left greater amounts of residue than those of lighter crude oils. In burns of lighter crude oils the amount of residue remaining was independent of the amount of oil burned, while for heavier crude oils the volume of residue remaining was proportional to the thickness of the slick burned.
- iii) In general, the densities of burn residues increased with increasing slick thickness. However, with the heavier oils residue density increased with slick thickness to a maximum and then declined.

The objective of the present study was to examine the chemical composition of the residue from small-scale burns of thick oil slicks in order to: i) describes the changes in chemical composition undergone by oils burning on water; and ii) determine how these changes are influenced by the conditions of the burn.

MATERIALS AND METHODS

Eight oils, listed below, were selected for the project. These were representative of the following: i) oils shipped by sea in North American waters; ii) oils that have been involved in tankship fires that resulted in the residue sinking; or iii) oils that had been used in recent in-situ burning field research studies. These oils were as follows: 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; and viii) automotive diesel. The physical properties of these oils are given Buist et al. (1995b).

Small-scale burns tests were conducted with each of the test oils. Tests involved burning 40-cm diameter pools of oil on water. For each oil, slicks of 5, 10 and 15 cm in thickness were burned. Two of the oils, Arabian Light crude oil and Mayan crude oil were artificially weathered to two degrees of evaporation by bubbling air through them at room temperature. 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 methods used in the test burns were reported in detail in Buist et al. (1995b).

All crude oils, evaporated crude oils and burn residues were chemically characterized using a common method to provide a measurement of: i) composition of each in terms of proportion of constituents in each of the boiling ranges Initial Boiling Point (IBP) to 204°C, 204°C to 538°C, and greater than 538°C.; and ii) chemical composition in terms of total saturates, total aromatics, total resins, and total asphaltenes in each boiling point range of 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 Analysing the IBP to 204°C fraction by the Fluorescence Indicator Absorbtion Method (FIA — ASTM D-1319) to provide measurements of total aromatics, olefins, and saturates in the fraction.
- Step 3 Analysing 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 Analysing 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 boiling point 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.

RESULTS AND DISCUSSION

Residues of all burns contained solids (at 163°C), except for those of diesel and Bonny Light crude oils. In the latter cases none of the residues contained solids. The amounts of solids present ranged from 0.5 to 34 percent of the total weight of residue. There did not appear to be any apparent correlation between the amount of solid material present and any of the experimental parameters. The composition of these solid materials was not determined. They could be: i) very high molecular weight hydrocarbons precipitated out of the oil as a result of the combustion process; ii) ash or soot from the combustion zone that has fallen back into the liquid oil during the burning process; or iii) salt crystals. In the analysis that follows a distinction was made between the solid and liquid residues (at 163°C). All of the chemical analyses reported here were conducted using only the portion of the residue that was liquid at 163°C.

The composition of the unburned oils and burn residues, in terms of boiling point fractions, is given in Table 1. Within this table the diesel fuels and fresh crude oils are listed

in order of increasing specific gravity. The analyses of the "weathered" oils are reported last. These data are based on the composition of the residue with the solid materials removed. The data show that none of the residues of any of the crude oil burns, regardless of slick thickness, contained any of the lower boiling point fractions (IBP to 204°C). Since the lower boiling point fraction is a common constituent of all of the unburned crude oils, this fraction is clearly completely driven off from the crude oils during burning. All of the burn residues of crude oils did contain some quantity of the middle boiling point fraction. Despite the fact that this fraction made up a major proportion, if not the majority, of the fresh oil, this fraction made up only a small fraction of the residue from most burns, indicating that this fraction too was preferentially driven off during burning. The residue of most crude oil burns was made up of heavy ends (the high boiling point fraction). This fraction made up only 7 to 40% of the composition of the parent oils, but this increased to 75 to 90+ percent in the burn residue, indicating selective concentration of these heavy ends took place in the oil during burning. These results indicate that in these studies burning is not an Equilibrium Flash Vaporization (EFV), but rather something between an EFV and a batch distillation. The process appears to be an "imperfect" Equilibrium Flash Vaporization.

In order to better understand the composition of the residue and changes that occur as a result of in-situ burning, Tables 2 through 6 were prepared. Tables 2, 4 and 6 show the proportional compositions of the major chemical groups (saturates, aromatics, resins and asphaltenes) in each of the parent oils, residues and boiling point fractions for three example oils, Arabian Heavy crude oil, Alberta Sweet Mixed Blend crude oil and diesel fuel. Tables 3 and 5 present the same information, but expressed in mass balance terms. The basis for Tables 3 and 5 is 100 grams of fresh oil burned.

The first three rows in Tables 3 and 5 show the weight of residue (total, solid and liquid) generated from each 100 g of fresh oil in 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 C₁₂). Note that these compounds are present only in the fresh crude oils; they are completely absent from the burn residues of the crude oils. The next three rows give the grams of saturates, aromatics and polar aromatics in the fraction that boils between 204°C and 538°C. These are all greatly reduced in the residues from the 5-cm burns and are almost completely absent from the residues from the 10- and 15-cm burns. The next four rows of data give the weights of the various types of compounds with boiling points greater than 538°C. These data show that although the constituents of this group are somewhat diminished in the residues, they are preserved to a far

greater degree than were the lower or middle boiling point fractions. The data from the burns of Alberta Sweet Mixed Blend, given in Table 5, show that the asphaltene fraction was almost completely preserved in the residue after the burns. This preservation of the asphaltene fraction was a common feature in burns of many of the fresh and weathered crude oils. This lends further credence to the "imperfect" EFV theory — the heavier compounds are concentrated in the residue and yet some of the heavier compounds have also been removed by combustion. The fact that the burn residues of crude oils are composed of largely of asphaltenes, high-boiling-point aromatics, resins and solid material (at 163°C) appears to account for their semi-solid rheology at ambient temperatures.

Table 6 presents the results of the chemical analyses of the parent oil and burn residues of diesel fuel. The residues contained no solids and, like the parent 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. 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 of burn residues of diesel fuel 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.

The data in Table 1 provide some insight into the relationship between slick thickness and the specific gravity of the burn residue. In general, the densities of burn residues increase with increasing slick thickness. The chemical analyses show that residues from burns of thicker crude oil slicks are composed almost totally of the high boiling point fraction, made up to a large extent by asphaltenes. However, the residues from the thinner slicks of the lighter crudes, at least, contained much greater proportions of the MBP fraction, which would explain the lower densities of these residues. Several of the heavier oils appear to produce residues with densities that increase with increasing slick thickness, but reach a maximum and then decline with further a further increase in thickness. Specifically these are Arabian Heavy, and Mayan crude oils. It is believed that this apparent anomalous behaviour may be due to the onset of a long vigorous burn phase during the test with these oils. The combustion process during the vigorous burn

phase is fundamentally different than during steady burning, in that during vigorous burning droplets of liquid oil are propelled into the combustion zone above the slick where they vapourize and burn completely. This atomization process would not result in concentration of the heavy ends in the remaining slick, but would be a true EFV. The early onset of a vigorous burn phase would result in a burn residue with a lower density than would otherwise be expected. The results of the present chemical analyses neither confirm nor refute the hypothesis of the role of the vigorous burn phase in causing the apparently anomalous changes in residue density in burns of thick slicks of heavy oils. It should be noted that the vigorous burn phase is probably an artifact of this type of apparatus and would not occur during actual in-situ burns at sea.

The burns conducted using weathered oils, Arabian Light and Mayan crude oils, reported in Buist et al. (1995b), showed that densities of residues of weathered oils were greater than those of the fresh oils. The chemical analyses of the unburned oils (Table 1) show that artificial "weathering" selectively depletes the lower boiling point fraction of these oils. The results in Table 1 also show that, as was the case with fresh crudes, burning of these weathered oils completely depletes the lower boiling point fraction of weathered oils and greatly diminishes the concentration of the middle boiling point fraction. The data show that the burn residues of "weathered" oils are more greatly depleted in the middle boiling point fraction than are the burn residues of fresh oils. This would appear to explain the greater densities of the burn residues of the "weathered" oils.

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 have shown 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 and has greatly reduced both the amount and concentration of the middle boiling point fraction (204°C to 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 greater than 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 and bioavailability of these high boiling point 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.

SUMMARY AND CONCLUSIONS

1. None of the burn residues from any of the crude oils contained any volatiles (with boiling points up to 204°C or approximately C₁₂); 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.
2. For most of the crudes, the asphaltenes, high-boiling-point (HBP) aromatics and resins appeared to be preserved and concentrated in the burn residue. Asphaltenes, HBP aromatics 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 as observed in Buist et al. (1995b).
3. The process occurring during in-situ burning appears to be a combination of Equilibrium Flash vapourization and batch distillation, because it results in both the progressive concentration of the heavier non-volatile compounds of the crude in the residue as well as the loss of some of the heavy ends. The concentration of the heavier, non-volatile components results in increased residue density and explains the semi-solid or near-solid rheology of the residue of the crude oils.
4. 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.

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**TABLE 1. Percent Composition of Unburned Oils and Burned Residues
by Boiling Point Fraction**

Oil Type	Treatment	Weight of Residue, grams	Composition (Weight %)		
			IBP to 204°C	204°C-538°C	> 538°C
Diesel	Fresh Oil	-	18.3	81.7	0
	5 cm burn	72	1.4	98.6	0
	10 cm burn	72	1.8	98.2	0
	15 cm burn	46	4.4	95.6	0
ASMB(*)	Fresh Oil	-	21.8	63.6	14.5
	5 cm burn	615	0	25.7	74.3
	10 cm burn	289	0	7.6	92.4
	15 cm burn	577	0	4.0	95.9
Bonny Light	Fresh oil	-	20.6	71.8	7.6
	5 cm burn	513	0	41.5	58.5
	10 cm burn	503	0	14.7	85.3
	15 cm burn	no data	no data	no data	no data
Arabian Light	Fresh Oil	-	18.6	55.4	26.1
	5 cm burn	355	0	9.2	90.8
	10 cm burn	208	0	5.3	94.7
	15 cm burn	2032	0	6.5	93.5
Iranian Heavy	Fresh Oil	-	20.9	52.2	26.9
	5 cm burn	339	0	13.1	86.9
Alask North Slope	Fresh Oil	-	17.2	57.2	25.02
	5 cm burn	828	0	9.6	90.4
	10 cm burn	1055	0	6.3	93.7
	15 cm burn	1509	0	8.7	91.2
(*) Alberta Sweet Mixed Blend					

**TABLE 1. Percent Composition of Unburned Oils and Burned Residues
by Boiling Point Fraction (Continued)**

Oil Type	Treatment	Weight of Residue, grams	Composition (Weight %)		
			IBP to 204°C	204°C-538°C	> 538°C
Arabian Heavy	Fresh Oil	-	15.6	49.9	34.5
	5 cm burn	823	0	9.3	90.7
	10 cm burn	1969	0	8.2	91.8
	15 cm burn	1590	0	8.7	91.3
Mayan	Fresh Oil	-	14.2	45.6	40.2
	5 cm burn	1564	0	9.0	91.0
	10 cm burn	3062	0	14.1	85.9
	15 cm burn	5063	0	13.1	86.9
Arab Light	Fresh Oil	-	18.6	55.4	26.1
	5 cm burn	355	0	9.2	90.8
Arab Light (20% evap.)	Unburned Oil	-	9.1	61.5	29.5
	5 cm burn	912	0	5.4	94.6
Arab Light (31% evap.)	Unburned Oil	-	2.0	64.8	33.2
	5 cm burn	453	0	8.8	91.3
Mayan	Fresh Oil	-	14.2	45.6	40.2
	5 cm burn	1564	0	9.0	91.0
Mayan (12% evap.)	Unburned Oil	-	7.4	49.3	43.3
	5 cm burn	1662	0	6.5	93.5
Mayan (22% evap.)	Unburned Oil	-	0	50.2	49.8
	5 cm burn	1812	0	3.2	96.8

TABLE 2 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. (°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 3 Mass Balance Data for Arabian Heavy Crude

Based on 100 g of crude oil burned	Arabian Heavy			
	Crude	5 cm Burn	10 cm Burn	15 cm Burn
Weight of residue (g)		24.8	17.7	9.1
Weight of solid residue (g)		2.33	0.08	1.19
Weight of liquid residue (g)		22.46	17.61	7.90
Weight of IBP-204°C cut (g)	15.62	0.00	0.00	0.00
Weight of 204-538 °C cut (g)	49.88	2.07	1.44	0.68
Weight of 538 °C plus cut (g)	34.50	20.38	16.16	7.21
	@15°C @40°C			
Amount of saturates in IBP-204°C (mL)	16.53 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	0.75	0.51	0.24
Weight of aromatics in 204-538°C (g)	20.97	1.25	0.87	0.40
Weight of polar aromatics in 204-538°C(g)	0.85	0.06	0.04	0.03
Weight of saturates in 538°C plus (g)	3.78	1.26	1.02	0.60
Weight of aromatics in 538°C plus (g)	18.15	8.12	6.51	3.03
Weight of resins in 538°C plus (g)	3.88	1.66	1.94	0.74
Weight of asphaltenes in 538°C plus (g)	8.67	9.33	6.67	2.83
Total saturates (g)		2.01	1.54	0.85
Total aromatics (g)		9.38	7.39	3.44
Total polar aromatics (g)		0.06	0.04	0.03
Total resins (g)		1.66	1.94	0.74
Total asphaltenes (g)		9.33	6.67	2.83
Composition of Liquid residue				
Saturates (Wt %)		8.98	8.77	10.81
Aromatics (Wt %)		41.76	42.00	43.56
Polar Aromatics (Wt %)		0.28	0.26	0.40
Resins (Wt %)		7.41	11.06	9.38
Asphaltenes (Wt %)		41.54	37.88	35.83

TABLE 4 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.(°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 5. Mass Balance Data for Alberta Sweet Mixed Blend Crude Oil

Based on 100 g of crude oil burned	Alberta Sweet Mixed Blend			
	Crude	5 cm Burn	10 cm Burn	15 cm Burn
Weight of residue (g)		11.5	2.7	3.6
Weight of solid residue (g)		0.07	0.46	1.22
Weight of liquid residue (g)		11.42	2.23	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	0.16	0.095
Weight of 538°C plus cut (g)	14.48	8.49	2.06	2.27
	①15°C ②40°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)	0.20 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)	42.56	1.51	0.07	0.04
Weight of aromatics in 204-538°C (g)	19.46	1.30	0.08	0.04
Weight of polar aromatics in 204-538°C(g)	1.61	0.11	0.00	0.00
Weight of saturates in 538°C plus (g)	3.89	1.86	0.23	0.21
Weight of aromatics in 538°C plus (g)	6.83	4.22	0.79	0.81
Weight of resins in 538°C plus (g)	2.13	1.20	0.21	0.20
Weight of asphaltenes in 538°C plus (g)	1.61	1.20	0.82	1.04
Total saturates (g)		3.38	0.31	0.26
Total olefins (g)		0.00	0.00	0.00
Total aromatics (g)		5.52	0.87	0.85
Total polar aromatics (g)		0.11	0.00	0.00
Total resins (g)		1.20	0.21	0.20
Total asphaltenes (g)		1.20	0.82	1.04
Composition of Liquid residue				
Saturates (Wt %)		29.58	13.94	11.10
Olefins (Wt %)		0.00	0.00	0.00
Aromatics (Wt %)		48.34	39.25	36.19
Polar Aromatics (Wt %)		1.02	0.36	0.14
Resins (Wt %)		10.51	9.70	8.46
Asphaltenes (Wt %)		10.51	36.72	44.08

TABLE 6. 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.(°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