

Emissions From Mesoscale In-Situ Oil (Diesel)Fires: Emissions from the Mobile 1998 Experiments

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Abstract

A series of mesoscale burns were conducted in 1998 to assess fire-resistant booms, 12 of these were used to study emissions from diesel oil burns. Extensive sampling and monitoring were conducted to determine the emissions at nine downwind ground stations, one upwind ground station and at six side stations. Particulates were measured using high volume samplers and real time particulate analysers. Particulate samples in air were taken and analysed for Polycyclic Aromatic Hydrocarbons (PAHs). Water under the burns was analysed; small amounts of PAHs were found. The burn residue was analysed for PAHs as well. PAHs were at about the same concentration in the residue than in the starting oil, however there is a slight differential concentration increase in some higher molecular weight species in the residue. Combustion gases including carbon dioxide, sulphuric acid aerosols and sulphur dioxide were very low and in some cases undetectable. Volatile organic compound (VOCs) emissions were measured in Summa canisters. Over 100 compounds were identified and quantified, most concentrations were too low to be considered a health risk.

1.0 Introduction

Nine years of intensive laboratory and tank testing on the in-situ combustion of oil have indicated that the nature and concentrations of atmospheric emissions from in-situ burning of oil offshore will normally be an acceptable tradeoff when

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weighed against the environmental risks and cleanup costs of shoreline contamination.

In 1991, U.S. MMS began the sponsorship, in cooperation with several agencies, of a series of mesoscale burn tests. These tests were designed to measure a series of physical parameters as well as emissions. The facilities of the Fire and Safety Test Detachment at Little Sand Island situated at upper Mobile Bay, Alabama, were used. Environment Canada and the U.S. Environmental Protection Agency cooperated to set up a series of instruments and samplers to monitor all suspect emissions at this and several subsequent trials. In 1992, a similar series of experiments was set up to monitor these burns. In 1993, a major experiment was conducted offshore Canada to measure crude oil emissions. Analyses of these trials are reported in the literature (Fingas et al., 1999a). In 1997 another set of trials was conducted to measure the performance of fire resistant boom. All previous results are reported in the literature (Fingas et al., 1998, 1999a,b). This paper reports on the data from the 1998 trials involving diesel fuel. The burns themselves and the boom tests were sponsored by the United States Coast Guard for the purpose of testing fire-resistant containment booms. Environment Canada and the U.S. Environmental Protection Agency sponsored the emission-measuring campaign.

2.0 Experimental

The primary goal of this series of test burns was the evaluation of five fire-resistant booms under American Society for Testing and Materials (ASTM) protocols. In total six booms were tested and twelve in-situ burn experiments were monitored. To carry out this project a test tank was constructed on Little Sand Island. The tank had dimensions of 9.2 m (30 feet) width by 30.8 m (100 feet) length by 1.5 m (5 feet) depth. Wave generating equipment was installed at one end of the tank. Provisions were made to install the test boom in a circular pattern about the center of the tank. A supply line transported the fuel from the storage tank to the center of the test tank. A 38,000 L (10,000 US gallon) storage tank was located on the island to supply the fuel for the tests. The discharge outlet in the test tank was located near the center of the boom at the interface of the surface and water.

During these burns the Emergencies Science Division (ESD) of Environment Canada (EC), in collaboration with the U.S. Environmental Protection Agency (EPA-ERT), performed air, water and fuel monitoring and/or sampling. Air monitoring was carried out using an array of stationary air sampling equipment and real-time monitoring equipment. Water and diesel samples were collected manually from the test tank and stored for subsequent analysis.

Environment Canada and the EPA supplied a variety of ground based instruments for sampling the air. In total there were sixteen sampling stations. Sampling stations formed a grid pattern surrounding the test tank with the majority situated on the downwind side. Monitoring stations extend from 30 m to 90 m away from the center of the test tank. As well, three meteorological monitoring stations were positioned 90 m downwind from the test tank, 90 m upwind from the test tank and 75 m to one side of the test tank. Water, diesel and residue samples were collected at specified time periods throughout the testing program. Figure 1 illustrates the site layout with monitoring locations marked. Table 1 summarizes the test burns and Table 2 gives the weather conditions prevalent during the tests.

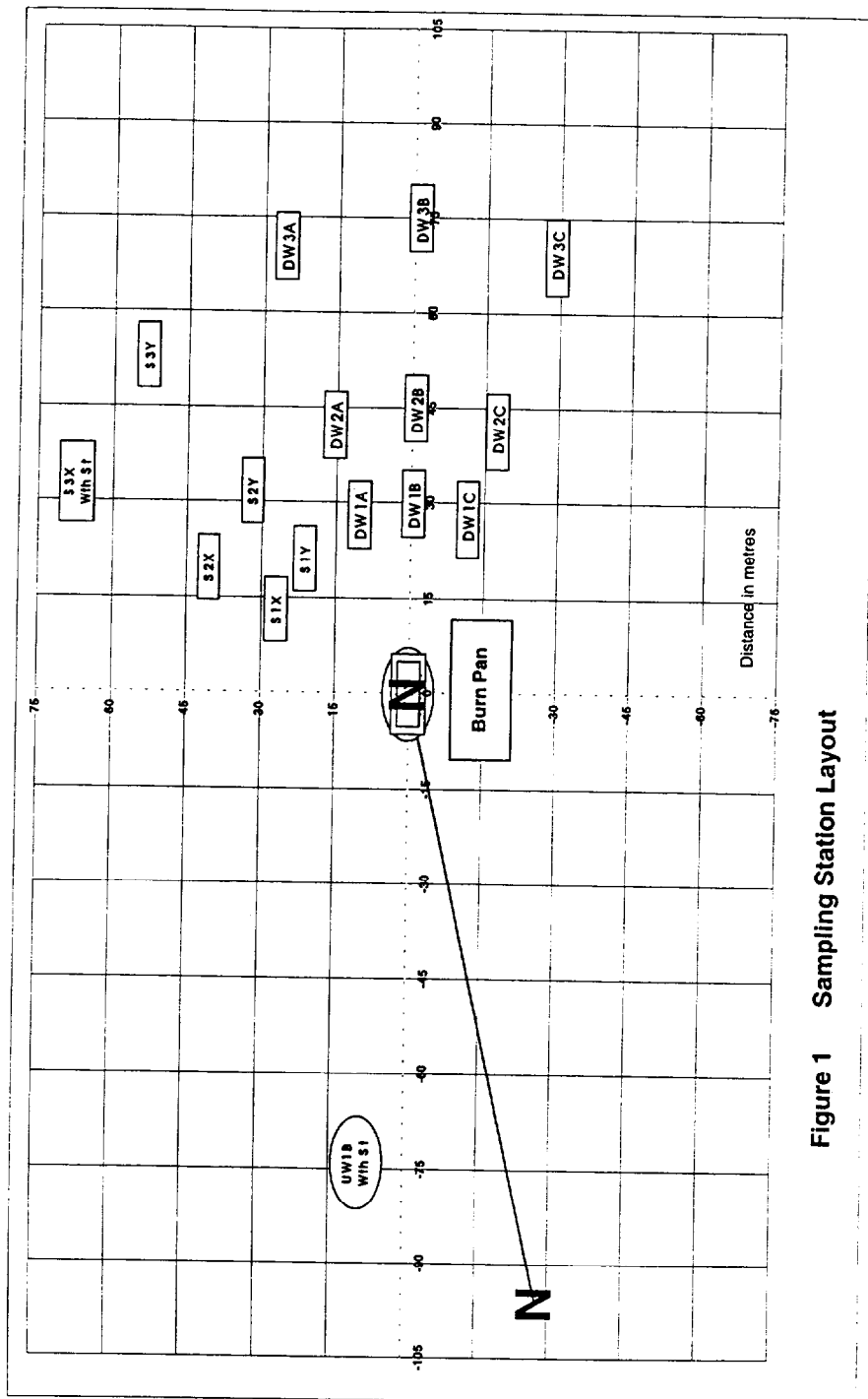


Figure 1 Sampling Station Layout

Table 1 Basic Experimental Parameters

Burn Number	Boom Number	Measurement Number	Time minutes	Diesel Amount (L)	Burn Area (m ²)	Burn Rate (mm/min)	Over Arrays?	Prime Arrays*
1	1	1	48	2517	14.3	3.7	yes	a/b, a/y, y/x
1	1a	2	120	3146		1.8	yes	b/c, c
2	1a	3	42	1575		2.6	yes	a,b,c
3	1a	4	43	1613		2.6	yes	a,b,c,b,b,c
1	2	5	5	144	10.5	2.7	no	
	background	6	60				background	
2	2	7	34	878		2.5	no	
1	3	8	62	2514	11.8	3.4	yes	a/b,y/x,a/b,b/c,c
2	3	9	59	2514		3.6	no	uw
3	3	10	63	2514		3.4	no	uw
1	4	11	71	3751	17.0	3.1	no	c/uw,uw
2	4	12	63	3308		4.4	yes	c
3	4	13	61	3308		4.6	yes	c
	background	14	60				background	
Average						3.2		

* This indicates over which sets of arrays the plume was passing during the burn

Table 2
Weather Conditions During the Burns

	Mean Wind Speed m/s	Mean Wind Direction deg North	Mean Air Temperature deg C	Barometer kPa	Relative Humidity %
Background (Sep 10)	3<4<4	65<78<98	24<24<25	101.5<101.6<101.7	75<76<77
Boom 1 Burn 1	1.4<2.6<3.8	21<339<301	28.0<28.4<29.1		
Boom 1a Burn 1	0.2<2.4<4.5	125<51<329	33.4<35.0<36.0		
Boom 1a Burn 2	0.4<2.2<3.9	56<14<324	28.8<29.5<30.1		
Boom 1a Burn 3	1.4<2.7<4.0	65<21<335	30.7<31.3<32.1		
Boom 3 Burn 1	0.0<2.1<3.9	93<19<263	30.7<31.1<31.6	100.5<100.5<100.5	49<51<56
Boom 4 Burn 2	2.5<4.5<7.4	24<49<72	25.3<25.5<25.7	101<101.1<101.2	72<77<84
Boom 4 Burn 3	1.9<3.5<5.2	22<50<77	26.3<27.0<27.4	101.2<101.2<101.2	54<56<60

Weather results reports in "Min<Ave<Max" format for the Burn Period (Wind sensors were 2 m high)

2.1 Oil, Residue and Water Samples for PAHs and Other Hydrocarbons

A 20 L (5 gallon) sample of the diesel fuel was collected from the fuel storage tank at the facility. The test protocol called for the continuous release of fuel to the tank. As such, a fuel sample was not collected prior to the initiation of the individual burns. The fuel was obtained from commercial ship fuelling operators located in Mobile, Alabama. The sample was collected in a new 20 L metal can meeting specifications for the storage and transportation of fuel products (Industrial Compliance Centre, Mississauga ON).

A sample of the residue was collected in a new, clean, 250mL wide mouth glass jar with a Teflon lined cap (Fisher Scientific, Nepean ON). A total of four residue samples were collected. One sample was taken following the completion of each boom test series. No sample was collected upon the completion of the testing on the fifth and final boom. All residue samples were collected manually by skimming the residue from the surface of the water in the test tank. Little residue was present and the residue layer itself was thin. The bottle was filled 3/4 full, capped, labelled, and then stored/transported in a refrigerator (15 °C).

For chemical analysis, approximately 0.4 gram of diesel fuel and residue was directly dissolved in hexane and made up to 5 mL with hexane. The concentrations of the diesel and residue samples were ~ 80 mg/mL. An aliquot containing 200 µL of oil solution was quantitatively transferred to the 3.0 g silica chromatographic column (which had been pre-conditioned with 20 mL hexane) for oil cleanup and fractionation. Additional 3 mL of hexane was applied to complete the transfer of oil. Hexane (12 mL) was used to elute saturate hydrocarbons, and 15 mL of 50% benzene in hexane (v/v) was used to elute aromatic hydrocarbons. Half of the hexane fraction (labeled F1) was used for analysis of total saturates, distribution of n-alkanes, isoprenoids including pristane and phytane, and of biomarker terpane and sterane compounds. Half of the 50% benzene fraction (labeled F2) was used for analysis of target petroleum-characteristic alkylated homologous PAHs and other EPA unsubstituted priority PAHs. The remaining halves of F1 and F2 were combined into a fraction (labeled F3) and used for the determination of total petroleum hydrocarbons (TPH). These three fractions were concentrated to appropriate volume using nitrogen blowdown in precalibrated centrifuge tubes. The fractions were then spiked with the appropriate internal standards and made up to accurate pre-injection volumes for GC analyses. The internal standard 5- α -androstane was added to F1 and F3 for determination of TPH, -alkanes and other interested individual aliphatic compounds; the internal standard d₁₄-terphenyl was added to F2 for quantitation of PAH compounds; and the IS C₃₀ $\beta\beta$ hopane was added to F1 for determination of biomarker compounds.

Prior to sample analysis, the instrument was calibrated with standard calibration mixture solutions. A 5-point calibration curve that confirmed the linear range of the analysis was established. The relative response factors (RRF) for each hydrocarbon component was calculated relative to the internal standard.

Two 1 L water samples were collected from the tank shortly after the tank was filled with water and prior to the commencement of the test program. This sample has been named the preburn sample. As a minimum, a 1 L sample of water was collected from the tank following the final burn test for four of the five booms which were evaluated. A single litre of water sample was collected following the testing of

the first boom. Two 1 L samples were obtained following the completion of the test series for the subsequent booms. No sample was collected upon the completion of the testing on the fifth and final boom. In total five water samples were collected. All water samples were manually collected at a depth of approximately 10 cm (4") below the surface for the water. The sample was collected and stored in a new, clean, 1 L amber Boston round bottle with a Teflon lined cap (Fisher Scientific, Nepean ON). The capped bottle was inserted into the water, opened, allowed to fill such that there was no head space in the bottle, recapped, removed from beneath the water, labeled, and stored/transported in a refrigerator at (15°C). The sampling location was generally about the center of the tank and the sample was collected during preparations to remove the boom.

Water sample extraction was conducted as follows: (1) each water sample was spiked with 100 µL PAH surrogate standards (four d_{10} - and d_{12} -PAHs, 10 ppm each), and 100 µL 200 ppm o-terphenyl in 1.0 mL of acetone, and sat for 15 minutes; (2) each water sample was then subsequently extracted 3 times with methylene chloride (200, 100, and 100 mL dichloromethane) for approximate 3 min each time; (3) the combined extract was dried by passing through the Na_2SO_4 layer and then concentrated to appropriate volume by rotary evaporation; (4) the solvent DCM was exchanged to hexane using the solvent exchange technique; (5) the extract was finally blown down with N_2 and made up to accurate 1.0 mL. The sample was analyzed in the same manner as noted for the oil and residue.

2.2 Real-time Air Monitoring - MIE RAM and DataRAM Portable Real-time Aerosol Monitor

The RAM and DataRAM are commercially-available pieces of equipment commonly used in the occupational health and safety industry. The RAM (MIE Inc, Bedford MA) portable real-time aerosol monitor allows measurement of aerosols and particulates continuously. The advantage of time information is the potential to correlate particulates with specific burn events, such as when the burn is initiated or extinguished.

Air is continuously drawn through the RAM sensor chamber at a rate of 2 L/minute. The instrument uses a pulsed Ga As semi-conductor LED to generate a near-infrared pulse centered at 940 nm. The scattered beam is detected with a silicon photo-voltaic-type diode with an integral low noise amplifier. The detector responds to scattered light deflected by 45-95 degrees. Filtered air is blown across detectors (0.3 L/minute) to keep the optical system clean. During these experiments, a cyclone pre-collector or optional omni-directional sampling head was affixed to the inlet to obtain the desired particulate fractions. The omni-directional sampling head is capable of measuring the total or 0-10 µm particulate fractions with the introduction of a 0-10 µm filter. The cyclone pre-collector limits the sampling to particulate larger than 2 µm however, the actual sampling fraction is 2-10 µm and the respective proportion of that fraction is based on a penetration curve. The two parameters that are controlled by the operator are the measuring range and the time constant. During these burn experiments the parameters were set to measure the total particulate fraction at a measurement range of 0-20 mg/m³ and a time constant of 2 seconds, thus sampling every 2 seconds.

For continuous monitoring tasks, such as burn tests, it was necessary to record

the data using an external data logger (Campbell Scientific CR10 Data Logger). The multiple values from the RAM were averaged over a period of one minute. Controls and settings which affect the digital display have a corresponding change to the analog output. Data recorded by the data logger was converted to concentration in $\mu\text{g}/\text{m}^3$. The instrument was operated using an external solar power source. The RAM units were placed at the specified location about the sampling field and barring instrument failure, remained on station for the duration of the project.

The DataRAM (MIE Inc, Bedford MA) is an updated version of the RAM. The operating principle is the same as for the RAM. The advantage of this unit over the RAM is its improved internal data logging and processing capabilities and versatility. The apparatus is capable of employing several different sampling head configurations. These are total particulate, the 0-10 μm particulate fractions or the 0.5 μm particulate fractions. In order to achieve the objectives of the study, the 10 μm fraction was used throughout the program. Measuring parameters such as the time constant and measurement range are selected during the initial set up of the unit and controlled by the internal software of the DataRAM. For this experiment the DataRAM and RAM were operated with similar air sampling rates. The instrument was operated using its internal rechargeable battery. Particulate concentration is given in units of $\mu\text{g}/\text{m}^3$ and the files were uploaded to a computer on a regular basis. The DataRAM units were placed at the specified location about the sampling field. Maintenance and calibration of the units were undertaken on a regular basis on the days during the burn program.

2.3 High Volume Air Sampler - Total Suspended Particulates (TSP)

Two types of high volume air sampling apparatus were employed in the 1998 trials to measure total suspended particulate matter in the air. The two units differ in construction but incorporate the same vacuum motor and magnehelic equipment. First was the high volume air sampler commonly call TSP sampler (Andersen Graseby/GMW, Smyrna GA). These units are described in Canadian and American reference methods for air monitoring. Total suspended particulates are classified as particles up to 25-50 μm size. The flow rate and geometry of this unit allows for the collection of particles ranging from 0.3 μm to 50 μm under normal operating conditions. The sample flow rate was recorded for each individual unit for each period of operation and was typically about 1.6 m^3/min (1600 L/min) with a typical volume of 100 m^3 passing through the filter per burn. The air samplers were located at the four main stations throughout the experiment. These were the three downwind 1 and one upwind station. They were manually turned on and off in conjunction with the burn program. A tared 20 X 35 cm glass fibre filter (Pacwill Environmental, Hamilton ON) was placed in the apparatus and used to collect sample. The second type of high volume sampler was the Model PS-1 PUF sampler (General Metal Works Inc., Cleves, OH). This instrument is designed to operate with two types of sampling media, a polyurethane foam plug for volatile compounds and a 102 mm circular filter for total suspended particulate. For these experiments only a 102 mm quartz glass filter (Pacwill Environmental, Hamilton ON) was used. These samplers were located at eight stations forming the second line of seven downwind stations all around the perimeter of the tank and at the upwind station. The volume of air which has passed through the PS1 high volume sampler must be manually calculated using

the procedure listed in the manufacturer's manual and results in a graph of Actual Flow Rate (CFM) versus Dial Gage Reading. During the field operations the PS1 samplers were manually turned on and off at the start and end of each burn respectively. Steps were taken to record the values on the Magnehelic Gage for all units shortly after the unit was turned on and again just prior to turning off the unit. This was carried out for each burn. Following the field operations the actual volume of air through each unit per burn was calculated. Using the appropriate prepared calibration curve and both the start and end Magnehelic reading, the actual flow rate was determined. The calibration curve gives the units of flow in cubic feet per minute. The time of a burn (in minutes) was used to determine the air volume in cubic feet. The average of the start and stop air volume values was then converted from ft^3 to m^3 using the conversion factor, 0.02832. The sample flow rate was recorded for each individual unit for each period of operation and was typically about $0.2 \text{ m}^3/\text{min}$ ($200 \text{ L}/\text{min}$) with a typical volume of 10 m^3 passing through the filter per hour long burn. Significant measures were taken to ensure adequate quality control was in place. The inside of the unit was rinsed with hexane prior to the start of the experiment. The filters were appropriately folded to reduce the risk of damage, placed in dedicated folders and stored in secure containers. Filters were weighed in a controlled environment designed and dedicated for this purpose. Background samples, field trip sample, instrument blanks etc were collected and used to evaluate the performance of the technique. After gravimetric determination of the TSP, the filters were extracted and analysed to determine the metal, total petroleum hydrocarbon and polycyclic aromatic hydrocarbon content of the particulate.

2.4 Sampling for Respirable Particulates (PM-10)

As in the case of TSP, values for particulate matter of $10 \mu\text{m}$ size and less (PM10) are specified in national ambient air quality standards. Two types of high volume air sampling apparatus were employed in the 1998 trials to measure the PM10 particulate fraction. First was the PM10 sampler (Andersen Graseby/GMW, Smyrna GA) was used to determine the amount of PM10 sized matter in the air. These units are described in Canadian and American reference methods for air monitoring for use in determining the respirable fraction of suspended particulate matter. The sample flow rate was recorded for each individual unit for each period of operation and was typically about $1.6 \text{ m}^3/\text{min}$ ($1600 \text{ L}/\text{min}$) with a typical volume of 100 m^3 passing through the filter per burn. The air samplers were located at the four main stations throughout the experiment. These were the three downwind 1 and one upwind station. Throughout the experiment and were manually turned on and off in conjunction with the burn program. A tared $20 \times 35 \text{ cm}$ ultra-pure quartz fibre filter (Pacwill Environmental, Hamilton ON) was placed in the apparatus and used to collect sample.

The second type of air sampling apparatus employed was the ACFM non-viable ambient particle sizing sampler or more commonly, the Cascade Impactor system (Andersen Instruments Inc., Atlanta, GA). Three units were deployed at the downwind 1A and 1 B position and the upwind station. This is an eight stage filter sampler in which each stage isolates an ever decreasing particulate fraction over the 0 to $10 \mu\text{m}$ range. Air flow is set and calibrated prior to operation in the field using an external pump. Circular Quartz filters specific to this unit were used (Pacwill

Environmental, Hamilton ON). The typical flow rate of the units was 0.023 m³/min (23 L/min) with a typical volume of 1.4 m³ passing through the filter per hour burn. Like the TSP measurements, extensive steps were put in place to ensure quality control. The PM₁₀ concentration was determined gravimetrically and then select filters were extracted and analysed to determine either the metal or total petroleum hydrocarbon and polycyclic aromatic hydrocarbon content of the PM₁₀ particulate fraction.

2.5 Air Sampling for Respirable Particulates (PM-2.5)

Recently the US E.P.A. has announced a proposed new air quality standard calling for the measurement of fine particles smaller than 2.5µm in size. A Partisol PM-2.5 sampler (Rupprecht & Patashnick, Albany NY) was used to determine the amount of PM-2.5 sized matter in the air. These were new units and were listed as meeting EPA sampling requirements immediately prior to their use in this project. Unlike the TSP and PM-10 samplers, the PM-2.5 is operated via an internal computer system. The air samplers were located at the four main stations throughout the experiment and were manually turned on and off in conjunction with the burn program. The sample flow rate and volume of air passing through the unit was automatically calculated. This data was recorded for each individual unit for each period of operation and was typically about 1 m³/hour (1000 L/hour or 16.7 L/min) with a typical volume of 1 m³ passing through the filter per burn. A tared 47 mm Teflon filter (CAE Instrument Rental, Palatine IL) was placed in the apparatus and used to collect sample. Like the other high volume filters, extensive steps were put in place to ensure quality control. The PM-2.5 concentration was determined gravimetrically and then the filters were extracted and analyzed to determine the metal, total petroleum hydrocarbon and polycyclic aromatic hydrocarbon content of the PM-2.5 particulate fraction.

2.6 Carbon Dioxide Monitoring - the Armstrong CD-1

This monitor is a commercially available piece of equipment commonly used in the occupational health and safety industry. The Armstrong CD-1 (Armstrong Monitoring Corporation Nepean, ON) units were located at six stations including the downwind 1 and upwind station and the sampling height was set at 1 m. The instruments were operated using an AC power source. The CD-1 units were placed at a noted location about the sampling field and barring instrument failure, remained on station for the duration of the project. Maintenance and calibration of the units were undertaken on a regular basis in co-ordination with the days in which the burn program was carried out.

The CD-1 CO₂ detector employs a non-dispersive infra-red (NDIR) detector to quantify the concentration of the gas in the air. An internal pump draws the sample at a rate of 1 L/min. A 4 m section of Teflon tubing was attached to the intake of all units. The Armstrong instrument was connected to an external data logger (Campbell Scientific CR10 Data Logger, Calgary AB) which were set up to record data continuously and report 1 minute averages. The instruments were turned on at an adequate time period prior to the start of the burn program to permit the units to stabilize. Also, they were allowed to continue to operate for an extended period of time following the completion of the burn trial. This permitted the evaluation of the

performance and responsiveness of the monitors. Data recorded by the external data logger for the CD-1 was converted to concentration in ppm using calculated formulations.

2.7 Carbonyls

To obtain a sample for analysis, a Gilian Aircon2 pump (Gilian Instrument Corp, West Caldwell NJ) was used to draw an air sample through a DNPH (2,4 dinitrophenylhydrazine) silica cartridge (Millipore Corporation, Milford MA) attached via Tygon tubing to the pump. The cartridge is a Waters Sep-pak containing 350 mg of silica coated with 1.0 mg DNPH. The flow rate of the pump was set at 1 L/min with an air volume of approximately 60 L passing through the cartridge over the hour long burn. The flow rate of the pump was calibrated on a regular basis. Trip, field and calibration blank samples were collected. The sampling apparatus was manually turned on and off at times corresponding to the start and end of the individual burn tests. Cartridges were kept frozen prior to use and the sample was placed in an amber vial and replaced into the freezer until analyzed. The cartridges were analyzed at Environment Canada's, Environmental Technology Centre by for aldehydes and ketones using a Hewlett-Packard 1090 High Pressure Liquid Chromatograph (HPLC).

2.8 VOCs in Summa Canisters

To monitor the VOC concentration in air an array of 6L, stainless-steel SUMMA canisters were located about the burn pan. The canisters were pre-evacuated to 0.05 mm of Hg. The flow controller (adjustable restricted orifice) is adjusted to known flow rate to collect approximately 4.5 Litres of sample (volume after which the intake of the canister is no longer linear). Summa canisters were placed at five stations. Sample canisters had a flow rate of 25 cc/min and remained at a station for a total of three 1-hour burns. The sampling orifice were opened and closed manually in co-ordination with the start and end of each burn.

An aliquot of the air sample is withdrawn from the canister, the water is removed and the VOCs is concentrated prior to injection onto the head of a GC capillary column. The major components of this system include two electronic flow controllers (FC260 with RO-32 control box, Tylan Corp., Torrance, Ca), a Nafion PermaPure dryer, a six port Valco™ gas valve, a cryogenic preconcentration trap and a sub-atmospheric temperature programmable gas chromatograph equipped with a quadruple mass selective detector (GC-MSD).

Canisters which are returned from the field at atmospheric or sub-atmospheric pressures following sampling must be pressurized prior to analysis. The canister is filled to approximately 30 psi with clean humidified air and a dilution factor is calculated from a previously obtained calibration curve. All lines are evacuated and purged with clean humidified air prior to filling. A flow rate of approximately 200 mL/min. is maintained by an electronic mass flow controller and verified with a Gilian™ soap-film bubble flowmeter. A certified clean canister is also filled and serves as a blank.

The volume of sample aliquots is adjusted so that target compounds fall within the analytical system calibration range of each of the target compounds. This varies from 1 mL to 500 mL depending on the initial concentration of the sample. A

sample loop is used for 1 mL and 10 mL aliquots and a gas-tight syringe is used for 20 mL to 200 mL aliquots. Larger aliquots (250 mL to 1000 mL) are withdrawn from the cylinder for 10, 15, 20 or 30 minutes at a constant flow of 25 mL/min. The flow rate is maintained by electronic mass flow controllers and verified with a Gilian™ soap-film bubble flowmeter.

A Nafion PermaPure™ dryer is used to prevent blockage of the trap and/or capillary column by ice formation at reduced temperature. To prevent excessive moisture build-up and memory effects the dryer is heated to 100 °C and purged with clean dry air for 20 minutes following each sample injection.

2.9 CO₂ in Summa Canisters

The Summa canisters used for VOCs were also used for carbon dioxide analysis. A Hewlett Packard 5890 Gas Chromatograph with microvolume thermal conductivity detector was used with Hewlett Packard 3365 DOS ChemStation software. The injection was via a Valco 6-port gas sampling valve with 1.0 mL loop in heated enclosure. The column was a 7' x 0.125" Porapak R (80/100) with valve injection directly on column. The valve enclosure was maintained at 80 °C, the detector block at 200 °C and the oven temperature started at 25 °C, hold 2.5 min then ramped 25 °C/min to 180 °C, hold 2.8 min. The carrier was Helium at 40.0 mL/min. The TCD Reference was Helium at 60.0 mL/min.

The oven temperature program is primarily used to remove heavier compounds and water from the column before the next injection. The CO₂ peak emerges during the initial isothermal segment. The TCD was calibrated by injection of a known concentration of CO₂ in N₂ (4758 ppmv) obtained from Matheson Gas Products. To verify calibration linearity the CO₂ standard was dynamically diluted with CO₂ free N₂ using a master/slave mass flow controller system and various dilutions were analysed in the same manner as the samples. A small metal bellows vacuum pump was used to draw the sample into the loop from a TEDLAR bag. The pressure inside the loop was allowed to equilibrate with ambient pressure before injection onto the column. Since the canisters supplied were under vacuum, a gauge was used to measure the pressure inside the loop when attached to the canister. A pressure correction curve was prepared to correct the analysis results for reduced pressure. Both the ambient calibration curve and the pressure correction curve are given. Any canister with a pressure below 500 mm Hg could not be analysed due to the pumping capacity of the pump being used. For canisters with very low pressures (<250 mm Hg), the analysis is probably more representative of the gas used to clean and flush the canister than the sample taken.

2.10 Sulphur Dioxide and Sulphuric Acid Aerosol

Although carbon and hydrogen make up the large majority of the composition of an oil, sulphur containing compounds can have concentration values in the low percent range in crude oils. Diesel fuel contains little sulphur dioxide. During combustion the emission of sulphur dioxide, hydrogen sulphide and sulphuric acid, as toxic gases, may become a health and safety concern. Two methods were employed to monitor the concentration in air of these gases.

The concentration of sulfur dioxide as the acid aerosol, sulphuric acid, in air was measured using the impinger method. It consisted of drawing a known volume

of air through a filter cassette (37 mm MCE, 0.8 μ m) attached to the end of a Tygon tube. The other end of the tube was fastened to a 25 mL midget impinger (SKC Inc., Eighty-four PA) containing 15 mL of 0.3N hydrogen peroxide. A second piece of tube connected the midget impinger to sample pump (Gilian Instrument Corp, West Caldwell NJ). The flow rate of the Gilian 513A pump was set at 1 L/min and air volumes of approximately 60 L passed through the impinger over the hour long burn. The concentration of the hydrogen peroxide solution was verified and the flow rate of the pump was calibrated on a regular basis. Trip, field and calibration blank samples were collected. The sampling apparatus was manually turned on and off at times corresponding to the start and end of the individual burn tests. Samples were transferred to amber vials and refrigerated. Subsequent analysis was performed following the completion of the field trials by ESD. Analytical protocols were based on the National Institute for Occupational Safety and Health (NIOSH, 1978) method S308. In summary, the sulphuric acid solution, generated from the reaction of sulphur dioxide with hydrogen peroxide, is titrated with barium perchlorate using a thiorin indicator to determine the end point. From the measured concentration of the sulphuric acid, the reaction mechanism of hydrogen peroxide and sulphur dioxide and the volume of air through the solution, the concentration of sulphur dioxide in air is calculated. The detection limit of the procedure was 0.25 ppm and all sample analysis showed results less than detection limit.

Sulphur containing emissions from the in-situ burning of fuels often take the form an acid gas. The Zellweger/MDA Scientific Single Point Monitor (SPM) (Lincolnshire, IL) was employed to measure the respective concentration of sulphuric acid and sulphur dioxide in air. Two units were set up to measure sulphuric acid and two measured sulphur dioxide. One of each type was placed at the upwind station and the downwind station identified as DW2B. In summary, a Chemcasette containing treated indicator paper detects and quantifies very low concentrations of the gas. A microprocessor controls the exposure or sample period and interprets the response of the Chemcasette. Detection limits can be optimized through adjustment of the sample time and flow rate. All data is processed via an internal processor and converted to electronic format. The monitoring systems were coupled to CR10 data logger system and voltages recorded. Following the field work the data was processed to determine the concentration of sulphuric acid and sulphur dioxide in air. Gas calibration standards were used to establish a relationship between voltage output of the units and concentration of the standards. The manufacturer lists the detection range of these units as 5 to 200 ppb for sulphur dioxide and 26 to 750 ppb for sulphuric acid.

2.11 Weather Stations

Three portable environmental monitoring stations were set up at the experiment site to monitor local weather conditions. The stations simultaneously log several types of meteorological data. These are wind speed, wind direction, temperature, barometric pressure and relative humidity. Two of the stations were developed by Earth and Atmospheric Science, Inc (Geneq Inc., Montreal, QC). The third station was operated by National Institute of Science and Technology staff and consisted of the WeatherPak system (Coastal Environmental, Seattle, WA). One station was positioned 105 m upwind of the burn pan along the primary line of

instruments, the second was placed approximately 75 m southeast of the test tank and the third was located 90 m downwind of the test tank along the primary line of instruments.

3.0 Results and Discussion

3.1 Particulates

A large amount of data was collected and was summarized for interpretation. The appendix contains summary data on all the filter-collection and electronic particulate (RAM and DataRAM) measurements. Table A-1 contains the TSP or Total Suspended Particulate results from both a standard high volume sampler (TSP) and the PS-1 sampler, Table A-2 shows the PM-10 results and Table A-3 contains the summary PM-2.5 results. Table A-4 shows the RAM results and Table A-5 summarizes the DataRAM results. Table 3 presents the same summary of all particulate measurements taken at the same location. The filter measurements (TSP, PM-10 and PM-2.5) were corrected for background by subtracting the upwind measurement and the electronic measurements (RAM and DataRAM) were corrected by subtracting the before-burn values. It is important to recognize that the background readings of the RAM and DataRAM are often very high, as can be seen in Table A-4 and Table A-5.

The correlation between the various measurements are shown in Table 4. Table 5 shows the relationship between the various measurement techniques. The correlation is very high - mostly because the values range widely and the wide spread appears through the various measurements. This shows that PM-10 values for this type of burn are about the same as the TSP values, just a little greater as would be expected. The PM-2.5 values are about 2/3 of the TSP values and about 3/4 of the PM-10 values. The DataRAM values are significantly less than the PM-10 values from the standard unit, although the values correlate. Considering the high variability in these experiments, overall there was excellent agreement between the high-volume samplers.

The spatial aspects of the soot distribution were examined and this shows that as expected, that the downwind concentrations are highest at the closest measuring point directly downwind. Because of the variability of the winds in these trials, several sample stations recovered soot. This shows the expected 'hump' along the most frequent wind direction and the expected square-root decline in soot concentrations.

3.3 PAHs in Oil, Residue and Water

Table 6 shows the results of the PAH analysis of the oil and residue and for the PAHs in the water under the fire. It is apparent from the data that the distribution of the PAHs is different in the starting oil than in the residue and also in the water column. Table 6 shows that the total PAHs in the starting diesel fuel and the residues is about the same. The amount of phenathrenes and dibenzo thiophenes is somewhat increased whereas the naphthalenes are reduced by the combustion. The amount of larger PAHs, eg. benz(a)anthracene to benzo(ghi)perylene are increased from a low concentration to a measurable concentration by combustion. The relative concentrations of the alkylated PAHs are shown in Figure 2. This chart shows the typical trends for the alkylated PAHs after diesel combustion. The naphthalenes are

Table 3

Summary of Particulate Measurements

		TSP Std. Units	PM-10 Std. Units	PM-10 DataRam	PM-2.5 Std. Units
Boom 1 & Boom 1a	DW1A	121	93	60	49
	DW1B	134	119	101	98
	DW1C	159	85	33	75
	UW1B	89	87	7	54
Boom 3 Burn 1 + 2	DW1A	224	284		0
	DW1B	205	333		0
	DW1C	168	207		0
	UW1B	119	186		0
Boom 4 Burn 1 + 2 + 3	DW1A	40	121	2	0
	DW1B	121	166	6	0
	DW1C	1156	1247	1263	975
	UW1B	16	110	4	64

Table 4

Correlation of Measurements Between Units

	TSP Std. Units	PM-10 Std. Units	PM-10 DataRam	PM-2.5 Std. Units
TSP Std. units	-	0.97	0.99	0.99
PM-10 Std. Units	-	-	0.99	0.99
PM-10 DataRAM	-	-	-	0.99

Table 5

Relationship of Measurements Between Units

Units	Ratio
TSP/PM- 10 Std.	1.2
TSP/PM- 10 RAM	0.12
TSP/PM- 2.5 Std.	0.67
PM-10 S /PM2.5	1.5

Table 6 PAH Analysis for Water, Diesel and Residue Samples

Sample Type	Control (µg/kg water)	Pre-burn water (µg/kg water)	Post-burn water (µg/kg water)	Residue (µg/g oil)	Diesel (µg/g oil)
PAH					
Naphthalene					
C0-N	0.273	0.021	0.04	89.1	311.7
C1-N	0.570	0.040	0.12	705.8	1805.4
C2-N	0.339	0.039	1.22	2258.9	4255.5
C3-N	0.121	0.044	17.12	2940.4	4055.0
C4-N	0.048	0.040	42.13	1825.6	1830.6
Sum of Naphthalenes	1.920	0.222	61	8526	14064
Phenanthrene					
C0-P	0.027	0.016	0.25	601.3	270.3
C1-P	0.085	0.043	17.91	2324.9	984.2
C2-P	0.121	0.057	103.84	2957.7	1123.8
C3-P	0.082	0.038	94.83	1549.4	511.9
C4-P	0.061	0.028	64.88	901.4	226.2
Sum of Phenanthrenes	0.377	0.182	282	8335	3116
Dibenzothiophene					
C0-D	0.002	0.002	0.30	352.0	602.0
C1-D	0.014	0.008	11.80	1157.1	1568.8
C2-D	0.018	0.011	62.18	1591.6	1688.5
C3-D	0.016	0.008	65.89	1055.0	859.7
Sum of Dibenzothiophenes	0.050	0.029	140	4156	4719
Fluorene					
C0-F	0.012	0.005	0.37	281.0	273.3
C1-F	0.015	0.013	5.28	865.5	855.1
C2-F	0.035	0.023	38.19	1621.5	1532.8
C3-F	0.035	0.026	67.59	1516.9	1213.1
Sum of Fluorenes	0.097	0.067	111	4285	3874
Chrysene					
C0-C	0.008	0.009	6.95	93.1	14.6
C1-C	0.019	0.010	9.42	114.5	19.8
C2-C	0.023	0.011	4.03	47.5	13.3
C3-C	0.017	0.005	1.19	15.7	5.9
Sum of Chrysenes	0.068	0.036	22	271	53
TOTAL	2.512	0.537	616	25572	25827
3-M-DBT (ratio)			1 : 0.81 : 0.54	1 : 0.72 : 0.171	0.69 : 0.13
C2D/C2P : C3D/C3P			0.60 : 0.69	0.54 : 0.68	1.50 : 1.68
2 pairs of m-phen			1.00	1.62	1.03
Other PAHs					
Biphenyl	0.066	0.016	0.02	15.20	44.45
acenaphthalene	0.003	0.001	0.12	14.15	5.25
Acenaphthene	0.007	0.001	1.17	20.28	18.58
Anthracene	0.002	0.003	2.37	18.57	3.32
Fluoranthene	0.016	0.014	5.04	13.30	0.48
Pyrene	0.007	0.008	25.46	53.49	3.02
Benz(a)anthracene	0.001	0.001	3.15	47.30	1.57
Benzo(b)fluoranthene	0.002	0.001	0.68	7.23	0.36
Benzo(k)fluoranthene	0.000	0.001	1.62	9.62	0.24
Benzo(e)pyrene	0.003	0.003	0.77	8.33	0.60
Benzo(a)pyrene	0.002	0.001	1.28	14.64	0.24
Perylene	0.007	0.001	0.19	2.02	0.18
Indeno(1,2,3cd)pyrene	0.001	0.001	1.02	6.31	0.30
Dibenz(a,h)anthracene	0.002	0.001	0.07	0.31	0.12
Benzo(ghi)perylene	0.001	0.000	0.84	7.97	0.18
TOTAL	0.120	0.054	44	239	79
Σ (other 3-6ring PAHs)			0.07	0.009	0.001
Σ (5 alkylated PAHs)					

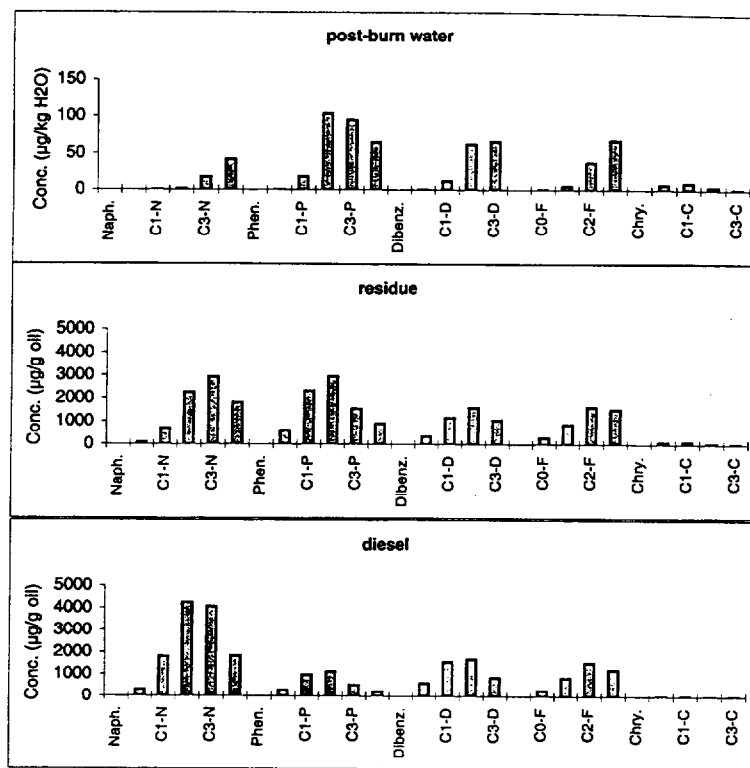


Figure 2 PAH Distribution in the Water, Diesel and Residue

reduced, phenanthrenes increased somewhat, the dibenzothiophenes reduced, fluorenes increased somewhat and the chrysenes are increased significantly. The overall concentration of the alkylated PAHs are about the same in the starting diesel and the residue. This is consistent with findings on previous diesel burns where the PAH distributions have been studied in detail (Wang *et al.* 1998). This same trend has not been observed in crude oil fires, however sufficient data have not been available to perform extensive studies.

3.4 Alkanes in Oil, Residue and Water

Table 7 shows the n-alkane amounts in the starting diesel fuel, the water and the residue. Figure 3 illustrates this distribution. These data show that the n-alkanes distribution is different in all three situations. The starting diesel fuel is weathered by the fire and the residue shows a greater concentration of the higher molecular size components and the water shows a distribution that is between these two.

3.5 PAHs on Particulates

Table 8 shows the PAH concentrations on particulate filters. Figures 4 and 5 show the distributions of these PAHs graphically. It is evident that the distribution of PAHs varies from sample device to sample device, although the difference may somewhat be influenced by the volume of material collected by each sampler type. It appears that there may be a higher volume of the larger PAHs on the smaller particles. Further study would be required to confirm this.

3.6 Carbon Dioxide

Table 9 summarizes the measurement of carbon dioxide using the Armstrong monitor and Table 10 the amount of carbon dioxide in the Summa canisters used for sampling VOCs and other gases. Because of the small size of the fire, there is only a low concentration of carbon dioxide, especially in comparison to the 1994 trials (Fingas *et al.* 1996). The ground concentration is generally between 0 and 40 ppm above the approximately 300 ppm background. The burn area in this trial was about 5 m² whereas the burn area in the 1994 trials was about 230 m². During the 1994 trials about 50 to 200 ppm carbon dioxide was measured. These data indicate a consistency in measured CO₂ compared to the size of the burn. Only one sampling station overlapped between the Summa sampling points and the Armstrong monitors, that of DW1B. The values of CO₂ between the two sampling methods are comparable.

The carbon dioxide concentrations around the burn are again much more evenly distributed than the soot concentrations as has also been found in previous burns. Especially when the wind has a low velocity, usually under about 5 m/s, the carbon dioxide is distributed all around the burn. As the wind velocity increases, it is increasingly distributed along the wind direction.

3.7 Sulphur Dioxide

Sulphur dioxide measurements taken both with the tapemeter instrument and an impinger which measures the acid form, H₂SO₄. The data for direct SO₂ show no measurable concentrations throughout the experiment. This is not surprising since the sulphur content of the diesel is very low and since most sulphur dioxide would be in an acid aerosol form not detectable by the instrument. The tapemeter did however

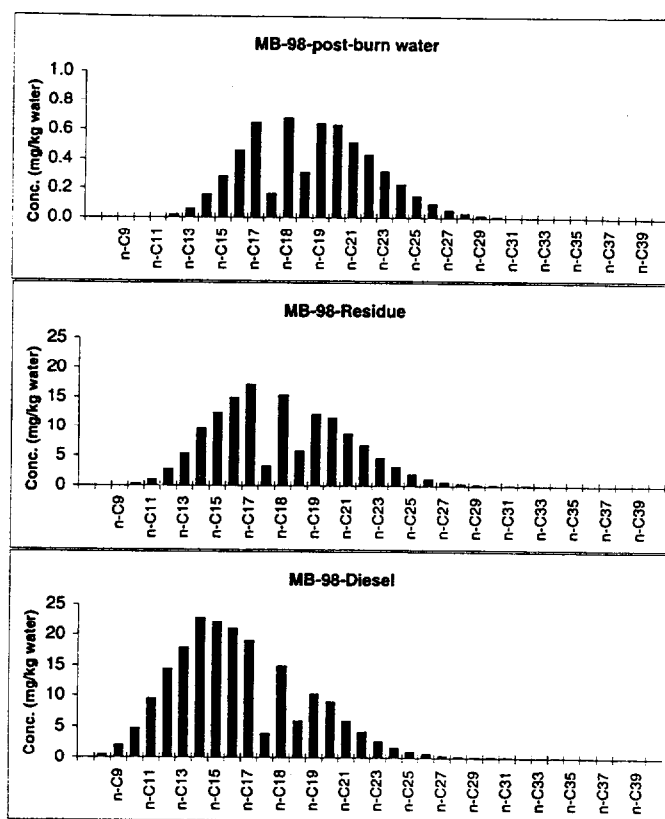


Figure 3 n-alkane Distribution in the Water, Residue and Diesel

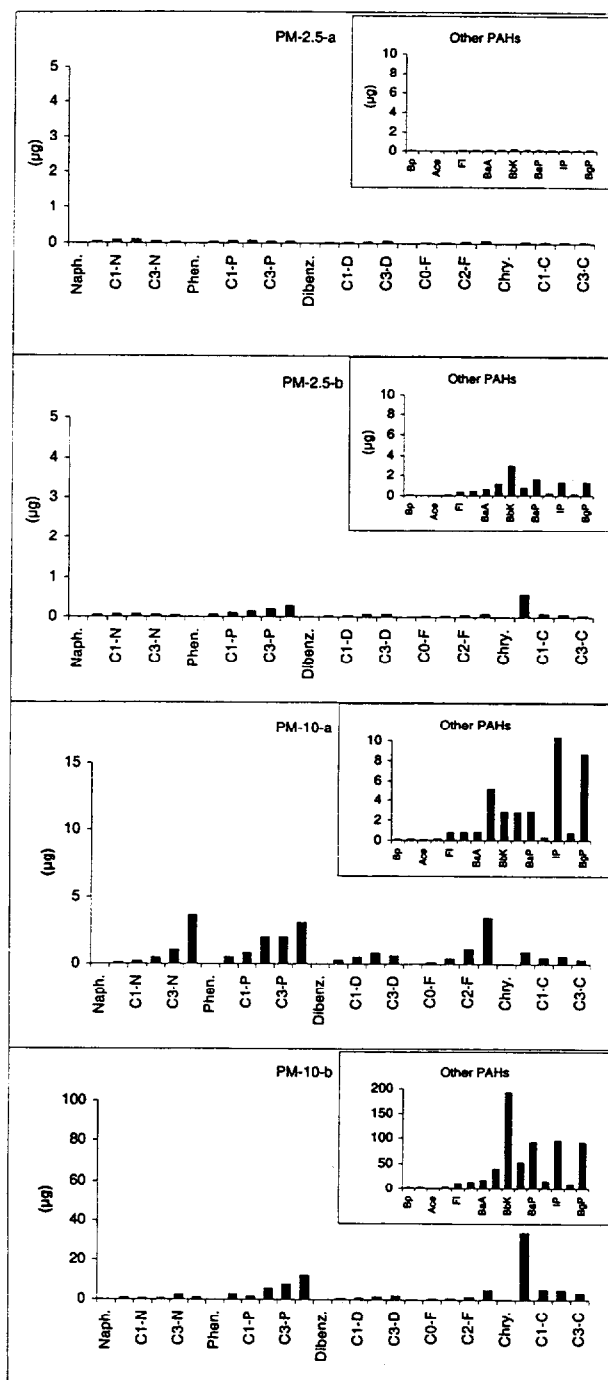


Figure 4 PAH Distribution in Respirable Particulate Samples

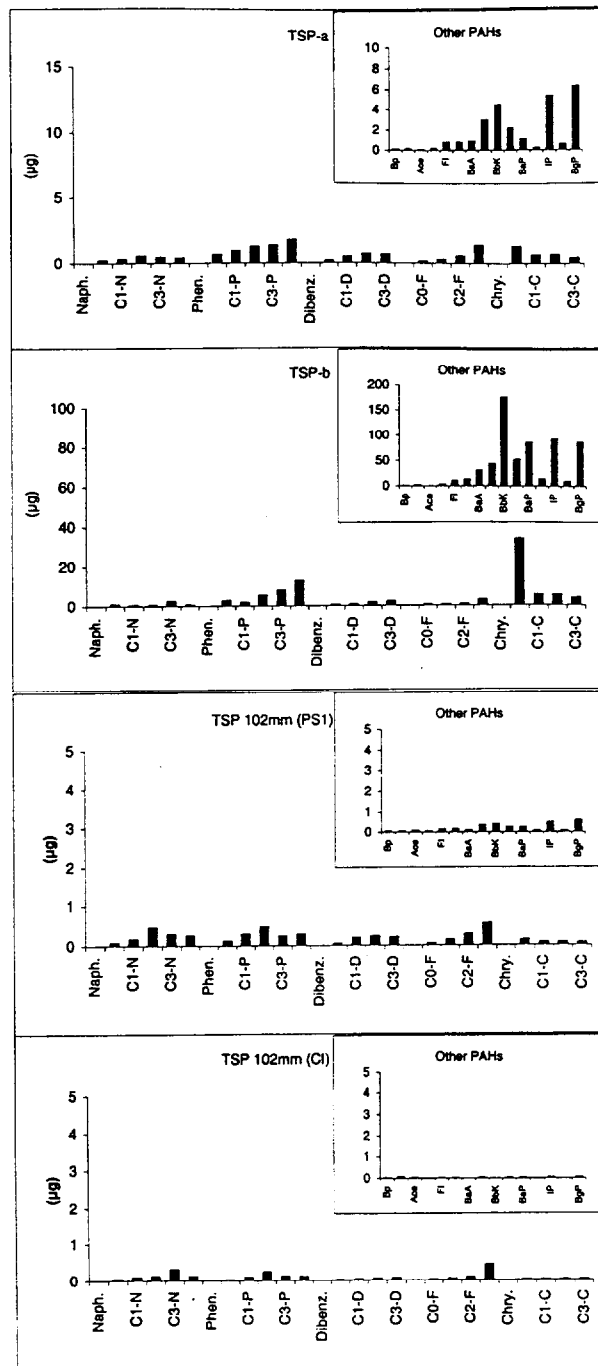


Figure 5 PAH Distribution in Total Suspended Particulate Samples

Table 7 **n-Alkane Distribution of Water, Diesel and Residue Samples**

Sample Type	Control	Pre-burn water	Post-burn water	Residue	Diesel
	(mg/kg water)	(mg/kg water)	(mg/kg water)	(mg/g oil)	(mg/g oil)
n-C8	ND	ND	ND	ND	0.42
n-C9	ND	ND	ND	ND	2.00
n-C10	ND	ND	ND	0.25	4.68
n-C11	ND	ND	ND	0.96	9.49
n-C12	ND	ND	0.02	2.68	14.37
n-C13	ND	ND	0.06	5.30	17.81
n-C14	ND	ND	0.15	9.52	22.77
n-C15	ND	ND	0.27	12.31	22.00
n-C16	ND	ND	0.45	14.89	20.91
n-C17	ND	ND	0.65	17.12	18.99
Pristane	ND	ND	0.16	3.22	3.85
n-C18	ND	ND	0.67	15.34	14.86
Phytane	ND	ND	0.30	5.73	5.90
n-C19	ND	ND	0.64	12.13	10.24
n-C20	ND	ND	0.63	11.47	9.00
n-C21	ND	ND	0.51	8.62	5.89
n-C22	ND	ND	0.42	6.69	4.16
n-C23	ND	ND	0.31	4.55	2.67
n-C24	ND	ND	0.22	3.11	1.69
n-C25	ND	ND	0.14	1.89	0.96
n-C26	ND	ND	0.09	1.13	0.63
n-C27	ND	ND	0.05	0.58	0.27
n-C28	ND	ND	0.03	0.33	0.14
n-C29	ND	ND	0.01	0.14	0.07
n-C30	ND	ND	0.01	0.07	0.05
n-C31	ND	ND	ND	0.04	0.02
n-C32	ND	ND	ND	0.03	ND
n-C33	ND	ND	ND	ND	ND
n-C34	ND	ND	ND	ND	ND
n-C35	ND	ND	ND	ND	ND
n-C36	ND	ND	ND	ND	ND
n-C37	ND	ND	ND	ND	ND
n-C38	ND	ND	ND	ND	ND
n-C39	ND	ND	ND	ND	ND
n-C40	ND	ND	ND	ND	ND
n-C41	ND	ND	ND	ND	ND
TOTAL	0.0	0.0	5.8	138.1	193.8
C17/Pristane	0.0	0.0	4.07	5.31	4.93
C18/Phytane	0.00	0.00	2.22	2.68	2.52
Pristane/phytane	0.00	0.00	0.52	0.56	0.65

ND: not detected

Table 8

PAH Analysis Results of Particulate Filters ($\mu\text{g}/\text{m}^3$ air)

Sample Type	TSP Boom 1	TSP Boom 4	PM-10 Boom 1	PM-10 Boom 4	PM-2.5 Boom 1	PM-2.5 Boom 4	PS1 Boom 1	CI Boom 4
Naphthalene								
C0-N	0.0001	0.0031	0.0001	0.0023	0.0015	0.0099	0.0002	0.0009
C1-N	0.0002	0.0010	0.0001	0.0009	0.0041	0.0160	0.0005	0.0024
C2-N	0.0003	0.0015	0.0003	0.0016	0.0048	0.0184	0.0014	0.0031
C3-N	0.0003	0.0085	0.0007	0.0081	0.0027	0.0129	0.0009	0.0087
C4-N	0.0002	0.0019	0.0026	0.0031	0.0015	0.0105	0.0008	0.0030
Sum	0.0012	0.0159	0.0039	0.0158	0.0146	0.0678	0.0038	0.0180
Phenanthrene								
C0-P	0.0004	0.0097	0.0003	0.0094	0.0013	0.0157	0.0004	0.0005
C1-P	0.0006	0.0057	0.0005	0.0054	0.0028	0.0282	0.0009	0.0022
C2-P	0.0008	0.0188	0.0014	0.0204	0.0035	0.0418	0.0015	0.0065
C3-P	0.0008	0.0280	0.0014	0.0284	0.0020	0.0580	0.0007	0.0032
C4-P	0.0011	0.0443	0.0022	0.0451	0.0021	0.0834	0.0009	0.0028
Sum	0.0037	0.1065	0.0059	0.1087	0.0117	0.2271	0.0043	0.0152
Dibenzothiophene								
C0-D	0.0001	0.0015	0.0002	0.0015	0.0004	0.0025	0.0001	0.0002
C1-D	0.0003	0.0020	0.0003	0.0021	0.0006	0.0058	0.0006	0.0006
C2-D	0.0004	0.0050	0.0006	0.0048	0.0016	0.0179	0.0007	0.0011
C3-D	0.0004	0.0074	0.0004	0.0064	0.0031	0.0205	0.0006	0.0017
Sum	0.0012	0.0159	0.0015	0.0147	0.0057	0.0466	0.0020	0.0035
Fluorene								
C0-F	0.0001	0.0009	0.0001	0.0008	0.0005	0.0020	0.0001	0.0002
C1-F	0.0002	0.0014	0.0003	0.0016	0.0010	0.0037	0.0004	0.0011
C2-F	0.0003	0.0019	0.0008	0.0046	0.0017	0.0114	0.0008	0.0021
C3-F	0.0009	0.0101	0.0025	0.0175	0.0032	0.0213	0.0017	0.0118
Sum	0.0015	0.0143	0.0036	0.0244	0.0064	0.0384	0.0030	0.0152
Chrysene								
C0-C	0.0008	0.1182	0.0006	0.1286	0.0014	0.1808	0.0004	0.0003
C1-C	0.0004	0.0189	0.0003	0.0184	0.0011	0.0212	0.0002	0.0004
C2-C	0.0004	0.0186	0.0004	0.0176	0.0010	0.0149	0.0002	0.0004
C3-C	0.0003	0.0130	0.0002	0.0120	0.0007	0.0076	0.0002	0.0005
Sum	0.0019	0.1687	0.0015	0.1767	0.0041	0.2244	0.0010	0.0016
TOTAL	0.010	0.321	0.016	0.340	0.043	0.604	0.014	0.054
Other PAHs								
Biphenyl	0.0000	0.0010	0.0000	0.0009	0.0005	0.0026	0.0001	0.0002
acenaphthalene	0.0001	0.0026	0.0000	0.0024	0.0003	0.0017	0.0001	0.0015
Acenaphthene	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0002	0.0003
Anthracene	0.0001	0.0069	0.0001	0.0070	0.0003	0.0077	0.0001	0.0001
Fluoranthene	0.0005	0.0343	0.0005	0.0370	0.0011	0.0945	0.0004	0.0002
Pyrene	0.0005	0.0427	0.0005	0.0465	0.0010	0.1186	0.0004	0.0004
Benz(a)anthracene	0.0006	0.1070	0.0006	0.0640	0.0005	0.1779	0.0002	0.0001
Benzo(b)fluoranthene	0.0019	0.1508	0.0037	0.1487	0.0037	0.3472	0.0010	0.0005
Benzo(k)fluoranthene	0.0029	0.6206	0.0020	0.7267	0.0076	0.9264	0.0013	0.0001
Benzo(e)pyrene	0.0014	0.1821	0.0020	0.1971	0.0029	0.2320	0.0007	0.0003
Benzo(a)pyrene	0.0007	0.3030	0.0020	0.3451	0.0023	0.4898	0.0007	0.0004
Perylene	0.0001	0.0504	0.0002	0.0565	0.0020	0.0610	0.0002	0.0001
Indeno(1,2,3cd)pyrene	0.0034	0.3275	0.0075	0.3580	0.0034	0.3945	0.0016	0.0010
Dibenz(a,h)anthracene	0.0004	0.0305	0.0005	0.0337	0.0005	0.0284	0.0002	0.0000
Benzo(ghi)perylene	0.0040	0.3051	0.0062	0.3432	0.0029	0.3910	0.0019	0.0012
TOTAL	0.0166	2.1646	0.0259	2.3670	0.0291	3.2734	0.0090	0.0064
Sum of all PAHs	0.03	2.49	0.04	2.71	0.07	3.88	0.02	0.06
Σ (other 3-6 ring PAHs)								
Σ (5 alkylated PAHs)	1.74	6.73	1.58	6.95	0.67	5.42	0.63	0.12

CI - Cascade Impactor

Table 9

Carbon Dioxide from the Armstrong CD-1

Above instrument Background

	Results: Min<Ave<Max in ppm					
	DW1A 16m, 176°N	DW1B 14m, 197°N	DW1C 16m, 219°N	S1X 34m, 132°N	S1Y 26m, 151°N	UW1B 74m, 23°N
Boom 1 Burn 1 (48 min)	0<6<10	0<6<9	0<3<9	0<3<6		0<2<9
Boom 1a Burn 1 (120 min)	0<9<47	0<9<47	0<9<38	0<22<56		0<8<20
Boom 1a Burn 2 (42 min)	0<6<18	0<5<16	0<7<25	0<4<8	0<4<9	0<3<6
Boom 1a Burn 3 (43 min)	0<7<22	0<8<17	0<10<18	0<5<11	0<6<14	0<3<6
Boom 3 Burn 1 (62 min)	0<21<51	0<20<40	0<16<36		0<25<89	0<23<42
Boom 4 Burn 2 (63 min)	0<4<7	0<8<17	0<22<64		0<7<14	0<4<10
Boom 4 Burn 3 (61 min)	0<17<33	0<18<30	0<13<38		0<25<52	0<25<50

Table 9

Carbon Dioxide from the Armstrong CD-1

Above Instrument Background

	Results: Min<Ave<Max in ppm					
	DW1A 16m, 176°N	DW1B 14m, 197°N	DW1C 16m, 219°N	S1X 34m, 132°N	S1Y 26m, 151°N	UW1B 74m, 23°N
Boom 1 Burn 1 (48 min)	0<6<10	0<6<9	0<3<9	0<3<6		0<2<9
Boom 1a Burn 1 (120 min)	0<9<47	0<9<47	0<9<38	0<22<56		0<8<20
Boom 1a Burn 2 (42 min)	0<6<18	0<5<16	0<7<25	0<4<8	0<4<9	0<3<6
Boom 1a Burn 3 (43 min)	0<7<22	0<8<17	0<10<18	0<5<11	0<6<14	0<3<6
Boom 3 Burn 1 (62 min)	0<21<51	0<20<40	0<16<36		0<25<89	0<23<42
Boom 4 Burn 2 (63 min)	0<4<7	0<8<17	0<22<64		0<7<14	0<4<10
Boom 4 Burn 3 (61 min)	0<17<33	0<18<30	0<13<38		0<25<52	0<25<50

Table 10 **Carbon Dioxide in Summa Canisters**

		<u>Final Conc (ppm)*</u>	<u>Above Background¹ (ppm)</u>
Boom 1, 1A	DW1B	421	15
Boom 1, 1A	DW2B	424	18
Boom 1, 1A	DW3B	418	12
Boom 1, 1A	DW3B	406	0
Boom 1, 1A	UW1B	419	13
Boom 3	DW1B	444	55
Boom 3	DW2B	405	16
Boom 3	DW3B	399	10
Boom 3	DW3B	389	0
Boom 3	UW1B	401	12
Boom 4 during	DW1B	427	13
Boom 4 during	DW2B	416	2
Boom 4 during	DW2B	414	0
Boom 4 during	DW3B	416	2
Boom 4 during	UW1B	591	177
Boom 4 between	DW1B	414	21
Boom 4 between	DW2B	401	8
Boom 4 between	DW2B	393	0
Boom 4 between	DW3B	413	20
Boom 4 between	UW1B	432	39

*This is the total concentration found in the particular canister

¹ This is the total concentration less the lowest concentration in a given measurement set

record an average of 0.47 ppm of the acid form, H_2SO_4 , during the burn 2 for boom 2, at station DW2B. The impinger samples did not show detectable levels of sulphur dioxide, the limit of detection is 0.25 ppm for the impinger method.

3.8 Carbonyls

Carbonyls were measured using an activated absorption tube. The carbonyls measured include aldehydes and some ketones. Results from this measurement are presented in Table 11. These show that the following compounds are often above upwind and background levels: formaldehyde, acetaldehyde, acetone, propionaldehyde and Methyl Ethyl Ketone (MEK). These are common products of incomplete combustion from sources such as vehicles. The levels found here are above what would be expected in an urban area or seen in recent crude oil fires, however the levels are already near upwind levels at 75 m downwind of the fire. Furthermore, these compounds are present from many emission sources so their measurement at sites like Mobile, near industrial activity, is difficult.

3.9 VOCs

VOCs were measured using multiple gas chromatographic techniques on samples taken from Summa canisters. One-hundred and forty-eight substances were analysed. The results of these analyses are given in the Appendix, Table A6. The values are uncorrected. Compounds which were not detected were removed from the list as were halogenated compounds. Table 12 summarizes the VOC results. This shows that the average VOC concentrations are very low and constitute some typical VOCs that would be in the background of an urban site such as this one.

4.0 Summary and Conclusions

4.1 Particulates

The diesel burns produced an abundance of particulate matter. The amount of particulate matter decreased with distance downwind from the fire. Concentrations at ground level (1 m) were above normal occupational health limits ($150 \mu\text{g}/\text{m}^3$) only as far downwind as 30 to 75 m. This is related to burn area, which in this case was very small ($\sim 5 \text{ m}^2$). A typical contained fire would have an area 10 to 100 times this size. It was found that the concentrations of TSP, PM-10 and PM-2.5 were about the same at the 6 sites where precision instruments were co-located. This may be indicative that the soot particle is broken down by the measurement devices.

The various instruments used to measure particulates yielded about the same values at the same locations for the same burns. The electronic measuring instruments, the RAM and DataRAM, however required a full background correction with data from before and after the burn. After correction, the correlation of the RAM and DataRAM data with that of the precision instruments was acceptable.

4.2 PAHs

Diesel contains low levels of PAHs with smaller molecular size. These are largely consumed by the fire, as evidenced by lower concentrations both in the soot and in the burn residue. Larger PAHs are either created or concentrated by the fire. Larger PAHs, some of which are not even detectable in the Diesel fuel, are found both in the soot and in the residue. The concentrations of these larger PAHs are however

Table 11

Carbonyl Measurementsconcentrations in ($\mu\text{g}/\text{m}^3$)

	Boom 1	Boom 1 + Boom 1a	Boom 1+2+3
	DW1B (1 m)	DW2B (1 m)	UW1B (1 m)
	14m, 197°N	29m, 197°N	74m, 23°N
Formaldehyde	8.32	7.34	6.97
Acetaldehyde	11.27	6.94	9.99
Acrolein	0.00	0.00	0.00
Acetone	11.81	10.56	12.49
Propionaldehyde	2.31	1.41	2.51
Crotonaldehyde	1.15	1.25	1.28
MEK	2.71	1.76	2.73
Benzaldehyde	1.62	1.36	1.29
Isovaleraldehyde	0.00	0.00	0.00
2-Pentanone	0.00	0.00	0.00
Valeraldehyde	0.58	0.21	0.46
o-Tolualdehyde	0.00	0.00	0.00
m-Tolualdehyde	2.14	1.54	1.85
p-Tolualdehyde	0.00	0.00	0.00
MIBK	0.00	0.00	0.00
Hexanal	1.03	0.00	0.44
2,5-Dimethylbenzaldehyde	0.00	0.00	0.00

*Data has been corrected with the Average value of the Instrument blanks and Trip blank***Background (Sept 14)**

	DW1B (1 m)	DW2B (1 m)	UW1B (1 m)
	14m, 197°N	29m, 197°N	74m, 23°N
Formaldehyde	3.22	2.68	3.04
Acetaldehyde	4.35	4.90	5.09
Acrolein	0.00	0.00	9.60
Acetone	6.25	2.97	5.78
Propionaldehyde	1.50	1.20	1.57
Crotonaldehyde	0.00	0.00	0.00
MEK	1.41	-0.69	1.34
Benzaldehyde	0.00	0.00	0.00
Isovaleraldehyde	0.00	0.00	0.00
2-Pentanone	0.00	0.00	0.00
Valeraldehyde	0.00	0.00	0.00
o-Tolualdehyde	0.00	0.00	0.00
m-Tolualdehyde	0.00	0.00	0.00
p-Tolualdehyde	0.00	0.00	0.00
MIBK	0.00	0.00	0.00
Hexanal	0.00	0.00	0.00
2,5-Dimethylbenzaldehyde	0.00	0.00	0.00

Table 12 Volatile Organic Compounds (VOCs)

Average Concentrations in $\mu\text{g}/\text{m}^3$	
Propane	5.8
2-Methylbutane	4.9
Butane	4.8
Toluene	3.4
m/p-Xylene	3.2
Pentane	3
Isobutane (2-Methylpropane)	2.6
n-Hexane	1.9
Dodecane	1.4
1-Butene/2-Methylpropene	1.2
1-Propene	1.1
o-Xylene	1.1
Isoprene (2-Methyl-1,3-Butadiene)	1
Benzene	1
Ethylbenzene	1
3-Methylpentane	0.9
3-Methylhexane	0.9
Undecane	0.9
1-Heptene	0.7
2,2,4-Trimethylpentane	0.7
Heptane	0.7
1,2,4-Trimethylbenzene	0.7
Decane	0.7
Methylcyclopentane	0.6
n-Nonane	0.6
2-Methylhexane	0.5
1-Octene	0.5
Methylcyclohexane	0.5
3-Ethyltoluene	0.5
2,3-Dimethylbutane	0.4
1-Hexene/2-Methyl-1-Pentene	0.4
2,3,4-Trimethylpentane	0.4
Octane	0.4
Naphthalene	0.4
1-Pentene	0.3
2-Methyl-2-Butene	0.3
2,2-Dimethylbutane	0.3
Cyclopentane	0.3
c-4-Methyl-2-Pentene	0.3
Cyclohexane	0.3
2,3-Dimethylpentane	0.3
2-Methylheptane	0.3
3-Methylheptane	0.3
Styrene	0.3
4-Ethyltoluene	0.3

low and often just above detection limits.

4.3 Gases

Carbon dioxide is found at low levels and distributed broadly around the fire area, especially when there are low winds.

Sulphur dioxide is found in the acid aerosol form and only at low levels from fires of these size. In most cases, the levels were below the detection level of the equipment.

One-hundred and forty-eight volatile organic compounds were measured from samples taken in Summa canisters. The concentrations of VOCs are relatively low. Concentrations appear to be under human health limits even at the closest monitoring station.

Carbonyls were measured using a sensitive and specialized technique. The diesel burns produce low amounts of the small aldehydes (formaldehyde, acetaldehyde, etc.) and ketones (acetone, etc.). These would not be a health concern even close to the source fire.

4.4 Emission into the Water under the Burn

The water under the fire received hydrocarbons. The total petroleum hydrocarbons rose by as much as 120 ppb or by as little 10 ppb. These are not high concentrations since the burns were conducted using a limited amount of water. Some PAHs could be detected in the water. Large n-alkanes were measured in the water column and their concentration distributed compared to those in the starting oil and the residue. The distribution of larger n-alkanes was similar to that of a moderately-weathered diesel fuel.

5.0 References

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Table A-1**Total Particulates****A****Particulates from TSP Filter Results ($\mu\text{g}/\text{m}^3$)**

Monitoring Station I.D. Field Position	DW1A (1 m) 16m, 176°N	DW1B (1 m) 14m, 197°N	DW1C (1 m) 16m, 219°N	UW1B (1 m) 74m, 23°N
Boom 1 & Boom 1a	121	134	159	89
Boom 3 Burn 1 + 2	224	205	168	119
Boom 4 Burn 1 + 2 + 3	40	121	1156	16
Background (Sept 11)	<0	0	<0	<0

*Post weights corrected using control filters left in balance room***B****Particulates from PS-1 Filter Results ($\mu\text{g}/\text{m}^3$)**

Monitoring Station I.D. Field Position	DW2A (1 m) 30m, 176°N	DW2B (1 m) 29m, 197°N	DW2C (1 m) 31m, 219°N	S1X (1 m) 34m, 132°N
Boom 1 & Boom 1a	320	675	452	311
Boom 3 Burn 1 + 2	<0	<0	<0	184
Boom 4 Burn 1 + 2 + 3	138	444	1127	604
Background (Sept 11)	<0	<0	<0	<0

Monitoring Station I.D. Field Position	S2X (1 m) 53m, 132°N	S1Y (1 m) 26m, 151°N	S2Y (1 m) 41m, 151°N	UW1B (1 m) 74m, 23°N
Boom 1 & Boom 1a	453	435	306	446
Boom 3 Burn 1 + 2	59	<0	<0	200
Boom 4 Burn 1 + 2 + 3	415	593	300	582
Background (Sept 11)	37	150	146	270

Post weights corrected using control filters left in balance room

Table A-2**Respirable Particulates - PM-10**Particulates from PM-10 Filter Results ($\mu\text{g}/\text{m}^3$)

Monitoring Station I.D. Field Position	DW1A (1 m) 16m, 176°N	DW1B (1 m) 14m, 197°N	DW1C (1 m) 16m, 219°N	UW1B (1 m) 74m, 23°N
Burn				
Boom 1 & Boom 1a	93	119	85	87
Boom 3 Burn 1 + 2	284	333	207	186
Boom 4 Burn 1 + 2 + 3	121	166	1247	110
Instrument Blank ($\mu\text{g}/\text{filter}$)	<0	<0	<0	<0
Background (Sept 11)	479	429	344	438

*Post weights corrected using control filters left in balance room***Table A-3****Respirable Particulates - PM-2.5**Particulates from PM-2.5 Filter Results ($\mu\text{g}/\text{m}^3$)

Monitoring Station I.D. Field Position	DW1A (1 m) 16m, 176°N	DW1B (1 m) 14m, 197°N	DW1C (1 m) 16m, 219°N	UW1B (1 m) 74m, 23°N
Burn				
Boom 1 & Boom 1a	49	98	75	54
Boom 3 Burn 1 + 2	<0	<0	<0	<0
Boom 4 Burn 1 + 2 + 3	<0	<0	975	64
Background (Sept 11)	<0	282	<0	<0
Instrument Blank ($\mu\text{g}/\text{filter}$)	128	<0	<0	112
Trip Blank ($\mu\text{g}/\text{filter}$)	65			

Post weights corrected using control filters left in balance room

Table A4 Total Aerosol Particulates from the Ram

Above Instrument Background (µg/m³)													
Monitoring Station I.D.	DW2A (1 m)	DW3A (1 m)	DW2B (1 m)	DW3B (1 m)	DW2C (1 m)	DW3C (1 m)	S1X (1 m)	S2X (1 m)	S3X (1 m)	S1Y (1 m)	S2Y (1 m)	S3Y (1 m)	UW1B (1 m)
Field Position	30m, 176°N	60m, 176°N	20m, 197°N	50m, 197°N	31m, 219°N	60m, 219°N	34m, 132°N	53m, 132°N	91m, 132°N	28m, 151°N	41m, 151°N	71m, 151°N	74m, 23°N
Burn or Time													
Background (Sep 10)	0<9<17	0<7<16	0<3<33	0<21<39	0<7<54	0<5<40	0<4<19	0<2<6	0<2<4	0<5<11	0<2<6	0<17<33	0<3<5
Post-burn	2<10<21	0<6<16	0<1<4	0<20<34	0<5<13	0<6<15	0<3<5	1<2<7	1<2<3	2<4<9	-2<1<3	2<15<31	1<3<11
Boom 1 Burn 1													
Burn	0<50<501	0<11<62	0<4<9	2<10<27	0<5<11	0<6<13	0<8<165	0<7<25	0<7<16	0<195<1454	0<108<876	1<82<218	0<5<12
Post-burn	8<19<94	1<18<99	-2<4<28	0<14<35	0<4<8	2<9<19	2<7<12	0<9<22	8<16<22	9<15<21	9<15<22	-31<20<26	1<7<12
Boom 1a Burn 1													
Burn	0<23<308	0<20<122	0<10<110	0<30<259	0<36<358	0<28<344	0<5<11	0<4<7	0<9<20	0<11<260	0<3<52	11<60<137	0<4<15
Post-burn	0<16<25	1<16<28	2<10<118	5<28<95	2<44<269	6<31<199	2<6<8	3<5<7	1<11<16	4<13<21	2<3<12	-11<19<39	3<5<8
Boom 1a Burn 2													
Burn	0<41<460	0<35<454	0<57<349	0<43<333	0<4<9	0<16<45	0<4<9	0<4<15		0<22<395	0<7<122	0<15<158	0<3<7
Post-burn	9<13<23	0<8<16	8<13<19	16<21<27	4<6<11	11<18<30	7<8<10	5<7<10		1<4<8	5<6<8	3<11<20	5<8<7
Boom 1a Burn 3													
Burn	0<57<1168	0<40<685	0<215<3932	0<108<1258	0<11<126	0<11<64	0<4<7	0<3<6		0<6<68	0<4<9	0<11<23	0<3<7
Post-burn	-3<9<31	5<15<29	-6<11<249	17<41<156	1<7<17	-10<3<12	0<5<12	-2<2<9		3<8<28	1<4<14	3<14<29	2<4<7
Boom 3 Burn 1													
Burn		0<100<1275	0<55<861	0<76<1226	0<105<1441	0<36<576	0<61<1815	0<77<1952		0<283<8030	0<210<6336	0<226<5671	0<8<19
Post-burn		13<25<42	-3<10<46	5<19<78	3<32<406	-9<9<96	6<20<154	6<9<24		12<20<60	3<8<25	-6<10<24	-1<3<8
Boom 4 Burn 2													
Burn	0<12<27	0<12<32	0<4<11	0<23<53		0<1167<421	0<5<10	0<3<6	0<2<4	0<5<18	0<4<10	0<18<44	0<4<10
Post-burn	-3<12<28	1<17<30	-6<0<6	-16<16<43		-28<11<477	-1<7<13	-3<-1<4	0<1<2	2<11<21	-3<0<3	4<34<60	-1<1<3
Boom 4 Burn 3													
Burn	0<14<35	0<12<24	0<3<14	0<22<43	0<479<3280	0<199<1603	0<2<5	0<4<8	0<2<5	0<3<10	0<4<14	0<16<32	0<1<4
Post-burn	2<13<79	2<11<43	5<8<21	1<19<66	-1<49<498	-2<20<260	-1<2<6	4<6<14	0<1<3	-3<3<7	2<4<11	0<20<33	2<2<4

Table A5 **PM-10 Particulates from the DataRam**
Above Instrument Background (ppm)

Monitoring Station I.D. Field Position		DW1A (1 m) 16m, 176°N	DW1B (1 m) 14m, 197°N	DW1C (1 m) 16m, 219°N	UW1B (1 m) 74m, 23°N
	Time				
Background (Aug 28)	Burn	0<6<12		0<5<19	0<5<27
Burn					
Boom 3 Burn 1	Pre-burn	-1<7<22	-6<5<31	-1<1<11	-3<2<5
Boom 3 Burn 1	Burn	0<60<1212	0<101<1176	0<33<343	0<7<15
Boom 3 Burn 1	Post-burn	-2<4<34	8<19<177	-3<32<605	0<4<7
Boom 4 Burn 1	Pre-burn	0<1<1	1<2<3	0<3<5	0<2<4
Boom 4 Burn 1	Burn	0<2<5	0<3<6	0<20<166	0<3<9
Boom 4 Burn 1	Post-burn	-1<1<2	-3<0<4	0<3<9	-2<2<5
Boom 4 Burn 2	Pre-burn	-1<0<1	0<0<0	-75<-71<-65	-2<0<2
Boom 4 Burn 2	Burn	0<2<3	0<0<0	0<3240<12571	0<4<10
Boom 4 Burn 2	Post-burn	-1<0<5	0<0<0	-73<0<2071	0<2<4
Boom 4 Burn 3	Pre-burn	2<3<5	1<3<5	-2<0<4	3<4<5
Boom 4 Burn 3	Burn	0<2<4	0<14<562	48<531<3823	0<3<12
Boom 4 Burn 3	Post-burn	2<3<4	2<5<14	-5<48<592	1<3<5

Table A6		Volatile Organic Compounds (VOCs)	
Burn Identification		BOOM 1 AND 1A	BOOM 1 AND 1A
Monitoring Station I.D.		DW1B	DW2B
Field Position		14m, 197°N	29m, 197°N
Concentrations in $\mu\text{g}/\text{m}^3$			
VOC Total		108	67
1-Propene		1.889	1.193
Propane		9.891	11.131
Isobutane (2-Methylpropane)		2.575	2.301
1-Butene/2-Methylpropene		1.789	2.010
1,3-Butadiene		0.358	ND
Butane		5.436	5.145
t-2-Butene		0.202	0.125
2,2-Dimethylpropane		0.069	0.073
c-2-Butene		0.184	0.140
2-Methylbutane		6.386	6.180
1-Pentene		0.453	0.281
2-Methyl-1-Butene		0.257	ND
Pentane		4.683	4.162
Isoprene (2-Methyl-1,3-Butadiene)		2.046	1.873
t-2-Pentene		0.178	0.099
c-2-Pentene		0.188	0.091
2-Methyl-2-Butene		0.487	0.324
2,2-Dimethylbutane		0.433	0.260
Cyclopentene		0.083	0.055
Cyclopentane		0.381	0.267
2,3-Dimethylbutane		0.719	0.363
t-4-Methyl-2-Pentene		ND	ND
c-4-Methyl-2-Pentene		ND	ND
3-Methylpentane		1.815	0.828
1-Hexene/2-Methyl-1-Pentene		0.690	ND
n-Hexane		2.293	1.879
t-2-Hexene		ND	ND
2-Ethyl-1-Butene		0.152	ND
2,2-Dimethylpentane		ND	ND
Methylcyclopentane		1.190	0.428
2,4-Dimethylpentane		0.331	ND
2,2,3-Trimethylbutane		ND	ND
1-Methylcyclopentene		0.136	0.062
Benzene		1.553	1.188
Cyclohexane		0.620	0.292
2-Methylhexane		1.524	0.574
2,3-Dimethylpentane		0.766	0.270
Cyclohexene		ND	ND
3-Methylhexane		1.644	0.619
1-Heptene		1.000	ND
2,2,4-Trimethylpentane		1.624	0.398
t-3-Heptene		ND	ND
Heptane		1.518	1.051
2,2-Dimethylhexane		NDR	ND
Methylcyclohexane		1.277	0.633
2,5-Dimethylhexane		0.361	0.156

Table A6 Burn Identification Monitoring Station I.D. Field Position	Volatile Organic Compounds (VOCs)	
	BOOM 1 AND 1A	BOOM 1 AND 1A
	DW1B 14m, 197°N	DW2B 29m, 197°N
2,4-Dimethylhexane	0.427	0.111
2,3,4-Trimethylpentane	0.593	ND
Toluene	6.040	3.196
2-Methylheptane	0.837	0.375
1-Methylcyclohexene	0.117	ND
4-Methylheptane	0.440	ND
3-Methylheptane	0.793	0.289
c-1,3-Dimethylcyclohexane	0.286	0.141
t-1,4-Dimethylcyclohexane	0.152	0.080
2,2,5-Trimethylhexane	0.193	0.038
1-Octene	0.619	ND
Octane	1.002	0.609
t-1,2-Dimethylcyclohexane	0.264	0.106
c-1,4/t-1,3-Dimethylcyclohexane	0.113	0.037
Ethylbenzene	2.588	1.332
m/p-Xylene	8.509	4.887
Styrene	1.650	0.096
o-Xylene	2.925	1.300
n-Nonane	1.439	0.771
iso-Propylbenzene	0.147	0.092
3,6-Dimethyloctane	0.147	ND
n-Propylbenzene	0.353	0.239
3-Ethyltoluene	1.101	0.493
4-Ethyltoluene	0.550	0.302
1,3,5-Trimethylbenzene	0.953	0.312
2-Ethyltoluene	0.521	0.227
1,2,4-Trimethylbenzene	2.215	0.923
Decane	1.708	0.803
iso-Butylbenzene	0.069	0.052
sec-Butylbenzene	0.070	0.040
1,2,3-Trimethylbenzene	0.770	0.279
p-Cymene	0.254	0.211
Indan	0.186	0.081
1,3-Diethylbenzene	0.139	0.082
1,4-Diethylbenzene	0.457	0.257
n-Butylbenzene	0.119	0.076
1,2-Diethylbenzene	0.053	0.069
Undecane	3.487	1.112
Naphthalene	0.791	1.184
Dodecane	6.501	1.745
Hexylbenzene	0.217	0.284

ND = Not Detected

NDR = Not Detected due to incorrect ion ratio

Table A6			
Burn Identification		BOOM 1 AND 1A	BOOM 1 AND 1A
Monitoring Station I.D.		DW3B	UW1B
Field Position		59m, 197°N	74m, 23°N
Concentrations in $\mu\text{g}/\text{m}^3$	VOC Total	66	62
1-Propene		1.045	1.739
Propane		12.288	8.719
Isobutane (2-Methylpropane)		2.266	1.877
1-Butene/2-Methylpropene		1.049	1.788
1,3-Butadiene		0.127	ND
Butane		5.313	4.359
t-2-Butene		0.112	0.228
2,2-Dimethylpropane		0.084	0.059
c-2-Butene		0.097	0.267
2-Methylbutane		6.141	5.236
1-Pentene		0.223	0.445
2-Methyl-1-Butene		ND	ND
Pentane		4.394	3.699
Isoprene (2-Methyl-1,3-Butadiene)		2.070	2.861
t-2-Pentene		0.061	0.104
c-2-Pentene		0.097	0.152
2-Methyl-2-Butene		0.228	0.392
2,2-Dimethylbutane		0.266	0.207
Cyclopentene		0.031	0.051
Cyclopentane		0.267	0.240
2,3-Dimethylbutane		0.355	0.302
t-4-Methyl-2-Pentene		ND	ND
c-4-Methyl-2-Pentene		ND	ND
3-Methylpentane		0.933	0.961
1-Hexene/2-Methyl-1-Pentene		ND	0.444
n-Hexane		1.771	2.092
t-2-Hexene		ND	ND
2-Ethyl-1-Butene		ND	0.041
2,2-Dimethylpentane		ND	ND
Methylcyclopentane		0.418	0.611
2,4-Dimethylpentane		0.120	0.134
2,2,3-Trimethylbutane		ND	ND
1-Methylcyclopentene		0.028	0.037
Benzene		0.894	1.089
Cyclohexane		0.262	0.324
2-Methylhexane		0.571	0.421
2,3-Dimethylpentane		0.259	0.194
Cyclohexene		ND	ND
3-Methylhexane		NDR	NDR
1-Heptene		ND	0.320
2,2,4-Trimethylpentane		0.496	0.334
t-3-Heptene		ND	ND
Heptane		1.217	0.704
2,2-Dimethylhexane		ND	ND
Methylcyclohexane		0.775	0.338
2,5-Dimethylhexane		0.184	0.096

Table A6		
Burn Identification	BOOM 1 AND 1A	BOOM 1 AND 1A
Monitoring Station I.D.	DW3B	UW1B
Field Position	59m, 197°N	74m, 23°N
2,4-Dimethylhexane	0.154	0.095
2,3,4-Trimethylpentane	0.175	0.112
Toluene	3.760	2.561
2-Methylheptane	0.462	0.172
1-Methylcyclohexene	ND	ND
4-Methylheptane	0.200	0.094
3-Methylheptane	0.375	0.176
c-1,3-Dimethylcyclohexane	0.134	0.052
t-1,4-Dimethylcyclohexane	0.088	0.034
2,2,5-Trimethylhexane	0.047	0.039
1-Octene	ND	0.581
Octane	0.577	0.314
t-1,2-Dimethylcyclohexane	0.131	0.047
c-1,4/t-1,3-Dimethylcyclohexane	0.043	ND
Ethylbenzene	1.436	1.996
m/p-Xylene	5.960	7.135
Styrene	0.233	0.550
o-Xylene	1.624	1.537
n-Nonane	0.485	0.397
iso-Propylbenzene	0.067	0.068
3,6-Dimethyloctane	ND	ND
n-Propylbenzene	0.213	0.181
3-Ethyltoluene	0.452	0.422
4-Ethyltoluene	0.246	0.234
1,3,5-Trimethylbenzene	0.450	0.322
2-Ethyltoluene	0.183	0.200
1,2,4-Trimethylbenzene	0.793	0.716
Decane	0.453	0.453
iso-Butylbenzene	0.031	0.033
sec-Butylbenzene	0.027	0.029
1,2,3-Trimethylbenzene	0.211	0.174
p-Cymene	0.165	0.191
Indan	0.069	0.067
1,3-Diethylbenzene	0.043	0.037
1,4-Diethylbenzene	0.147	0.142
n-Butylbenzene	0.048	0.040
1,2-Diethylbenzene	ND	ND
Undecane	0.514	0.386
Naphthalene	0.310	0.320
Dodecane	0.674	0.326
Hexylbenzene	0.095	0.098

ND = Not Detected

Table A6

Burn Identification Monitoring Station I.D. Field Position	BOOM 3 DW1B 14m, 197°N	BOOM 3 DW2B 29m, 197°N
Concentrations in $\mu\text{g}/\text{m}^3$ VOC Total	163	59
1-Propene	1.209	1.281
Propane	9.349	5.209
Isobutane (2-Methylpropane)	9.894	2.230
1-Butene/2-Methylpropene	2.777	1.046
1,3-Butadiene	0.139	0.107
Butane	21.709	5.080
t-2-Butene	0.798	0.144
2,2-Dimethylpropane	0.077	0.069
c-2-Butene	0.637	0.153
2-Methylbutane	15.453	7.118
1-Pentene	0.702	0.324
2-Methyl-1-Butene	0.200	0.225
Pentane	5.811	4.025
Isoprene (2-Methyl-1,3-Butadiene)	0.074	0.468
t-2-Pentene	0.348	0.177
c-2-Pentene	0.350	0.186
2-Methyl-2-Butene	0.443	0.477
2,2-Dimethylbutane	0.937	0.396
Cyclopentene	0.154	0.108
Cyclopentane	0.975	0.330
2,3-Dimethylbutane	1.462	0.451
t-4-Methyl-2-Pentene	ND	ND
c-4-Methyl-2-Pentene	0.343	ND
3-Methylpentane	3.911	0.974
1-Hexene/2-Methyl-1-Pentene	0.343	0.304
n-Hexane	9.874	2.096
t-2-Hexene	0.077	ND
2-Ethyl-1-Butene	ND	0.040
2,2-Dimethylpentane	0.132	0.070
Methylcyclopentane	3.119	0.675
2,4-Dimethylpentane	0.572	0.194
2,2,3-Trimethylbutane	ND	ND
1-Methylcyclopentene	0.037	0.095
Benzene	2.625	1.397
Cyclohexane	1.637	0.245
2-Methylhexane	2.159	0.498
2,3-Dimethylpentane	1.234	0.371
Cyclohexene	ND	ND
3-Methylhexane	2.532	0.646
1-Heptene	0.800	ND
2,2,4-Trimethylpentane	4.083	0.682
t-3-Heptene	ND	ND
Heptane	1.731	0.821
2,2-Dimethylhexane	NDR	ND
Methylcyclohexane	1.956	0.345
2,5-Dimethylhexane	0.569	0.123

Table A6

Burn Identification Monitoring Station I.D. Field Position	BOOM 3 DW1B 14m, 197°N	BOOM 3 DW2B 29m, 197°N
2,4-Dimethylhexane	0.744	0.122
2,3,4-Trimethylpentane	1.320	0.252
Toluene	13.049	3.700
2-Methylheptane	0.924	0.275
1-Methylcyclohexene	ND	ND
4-Methylheptane	0.374	0.128
3-Methylheptane	0.914	0.293
c-1,3-Dimethylcyclohexane	0.171	0.070
t-1,4-Dimethylcyclohexane	0.122	0.050
2,2,5-Trimethylhexane	0.508	0.080
1-Octene	0.465	0.674
Octane	1.260	0.510
t-1,2-Dimethylcyclohexane	0.162	0.074
c-1,4/t-1,3-Dimethylcyclohexane	0.110	0.033
Ethylbenzene	3.545	0.802
m/p-Xylene	11.344	2.454
Styrene	ND	0.128
o-Xylene	5.117	0.872
n-Nonane	2.138	0.610
iso-Propylbenzene	0.206	0.083
3,6-Dimethyloctane	ND	ND
n-Propylbenzene	0.785	0.246
3-Ethyltoluene	1.705	0.640
4-Ethyltoluene	0.932	0.349
1,3,5-Trimethylbenzene	0.237	0.344
2-Ethyltoluene	0.615	0.297
1,2,4-Trimethylbenzene	1.624	1.069
Decane	1.646	0.767
iso-Butylbenzene	0.040	0.031
sec-Butylbenzene	0.045	0.037
1,2,3-Trimethylbenzene	0.253	0.258
p-Cymene	0.066	0.071
Indan	0.093	0.122
1,3-Diethylbenzene	0.066	0.121
1,4-Diethylbenzene	NDR	0.306
n-Butylbenzene	0.071	0.076
1,2-Diethylbenzene	0.033	0.045
Undecane	0.491	1.045
Naphthalene	0.089	0.430
Dodecane	0.096	1.139
Hexylbenzene	0.072	0.118

ND = Not Detected

Table A6			
Burn Identification		BOOM 3	BOOM 3
Monitoring Station I.D.		DW3B	UW1B
Field Position		59m, 197°N	74m, 23°N
Concentrations in $\mu\text{g}/\text{m}^3$ VOC Total		52	56
1-Propene		1.416	1.882
Propane		5.384	4.733
Isobutane (2-Methylpropane)		2.174	2.248
1-Butene/2-Methylpropene		1.110	1.632
1,3-Butadiene		0.125	0.319
Butane		4.731	4.496
t-2-Butene		0.168	0.184
2,2-Dimethylpropane		0.069	0.070
c-2-Butene		0.147	0.158
2-Methylbutane		6.702	6.666
1-Pentene		0.231	0.527
2-Methyl-1-Butene		0.222	0.226
Pentane		3.815	3.741
Isoprene (2-Methyl-1,3-Butadiene)		0.424	0.600
t-2-Pentene		0.152	0.185
c-2-Pentene		0.176	0.188
2-Methyl-2-Butene		0.443	0.464
2,2-Dimethylbutane		0.380	0.372
Cyclopentene		0.082	0.069
Cyclopentane		0.343	0.284
2,3-Dimethylbutane		0.441	0.421
t-4-Methyl-2-Pentene		ND	ND
c-4-Methyl-2-Pentene		ND	ND
3-Methylpentane		0.969	1.018
1-Hexene/2-Methyl-1-Pentene		0.190	0.640
n-Hexane		2.054	1.993
t-2-Hexene		0.070	0.052
2-Ethyl-1-Butene		0.039	ND
2,2-Dimethylpentane		ND	ND
Methylcyclopentane		0.496	0.510
2,4-Dimethylpentane		0.163	0.200
2,2,3-Trimethylbutane		ND	ND
1-Methylcyclopentene		0.067	0.067
Benzene		1.035	1.013
Cyclohexane		0.225	0.199
2-Methylhexane		0.557	0.613
2,3-Dimethylpentane		0.395	0.413
Cyclohexene		ND	ND
3-Methylhexane		0.633	0.677
1-Heptene		ND	0.480
2,2,4-Trimethylpentane		0.715	0.912
t-3-Heptene		ND	ND
Heptane		0.709	0.806
2,2-Dimethylhexane		NDR	NDR
Methylcyclohexane		0.326	0.330
2,5-Dimethylhexane		0.119	0.169

Table A6

Burn Identification Monitoring Station I.D. Field Position	BOOM 3 DW3B 59m, 197°N	BOOM 3 UW1B 74m, 23°N
2,4-Dimethylhexane	0.165	0.186
2,3,4-Trimethylpentane	0.220	0.340
Toluene	3.500	3.780
2-Methylheptane	0.241	0.300
1-Methylcyclohexene	ND	ND
4-Methylheptane	0.092	0.117
3-Methylheptane	0.247	0.311
c-1,3-Dimethylcyclohexane	0.062	0.069
t-1,4-Dimethylcyclohexane	0.052	0.054
2,2,5-Trimethylhexane	0.065	0.083
1-Octene	ND	0.469
Octane	0.382	0.483
t-1,2-Dimethylcyclohexane	ND	0.066
c-1,4/t-1,3-Dimethylcyclohexane	0.027	0.036
Ethylbenzene	0.723	0.785
m/p-Xylene	2.190	2.490
Styrene	0.084	0.095
o-Xylene	0.744	0.831
n-Nonane	0.383	0.435
iso-Propylbenzene	0.068	0.075
3,6-Dimethyloctane	ND	ND
n-Propylbenzene	0.200	0.200
3-Ethyltoluene	0.543	0.545
4-Ethyltoluene	0.305	0.301
1,3,5-Trimethylbenzene	0.287	0.288
2-Ethyltoluene	0.221	0.218
1,2,4-Trimethylbenzene	0.894	0.893
Decane	0.440	0.419
iso-Butylbenzene	0.032	0.030
sec-Butylbenzene	0.029	0.033
1,2,3-Trimethylbenzene	0.216	0.200
p-Cymene	0.083	0.102
Indan	0.087	0.091
1,3-Diethylbenzene	0.112	0.094
1,4-Diethylbenzene	0.178	0.208
n-Butylbenzene	0.060	0.057
1,2-Diethylbenzene	0.037	0.043
Undecane	0.511	0.401
Naphthalene	0.320	0.290
Dodecane	0.464	0.360
Hexylbenzene	0.097	0.099

ND = Not Detected

Table A6

Burn Identification	BOOM 4 BURN	BOOM 4 BURN
Monitoring Station I.D.	DW1B	DW2B
Field Position	14m, 197°N	29m, 197°N
Concentrations in $\mu\text{g}/\text{m}^3$ VOC Total	51	24
1-Propene	1.922	0.288
Propane	3.811	3.497
Isobutane (2-Methylpropane)	6.702	1.557
1-Butene/2-Methylpropene	1.022	0.522
1,3-Butadiene	0.428	ND
Butane	2.899	2.792
t-2-Butene	0.113	0.101
2,2-Dimethylpropane	0.046	0.053
c-2-Butene	0.116	0.066
2-Methylbutane	2.502	2.421
1-Pentene	0.159	0.097
2-Methyl-1-Butene	ND	ND
Pentane	1.918	1.914
Isoprene (2-Methyl-1,3-Butadiene)	0.721	0.878
t-2-Pentene	ND	ND
c-2-Pentene	ND	ND
2-Methyl-2-Butene	0.138	0.111
2,2-Dimethylbutane	0.154	0.183
Cyclopentene	0.029	0.030
Cyclopentane	0.164	0.113
2,3-Dimethylbutane	0.259	0.127
t-4-Methyl-2-Pentene	ND	ND
c-4-Methyl-2-Pentene	ND	ND
3-Methylpentane	0.431	0.493
1-Hexene/2-Methyl-1-Pentene	0.271	ND
n-Hexane	1.096	0.888
t-2-Hexene	ND	ND
2-Ethyl-1-Butene	ND	ND
2,2-Dimethylpentane	ND	ND
Methylcyclopentane	0.247	0.267
2,4-Dimethylpentane	ND	ND
2,2,3-Trimethylbutane	ND	ND
1-Methylcyclopentene	0.025	0.030
Benzene	0.987	0.591
Cyclohexane	0.110	0.109
2-Methylhexane	0.237	0.224
2,3-Dimethylpentane	0.141	0.122
Cyclohexene	ND	ND
3-Methylhexane	NDR	NDR
1-Heptene	ND	ND
2,2,4-Trimethylpentane	0.220	0.160
t-3-Heptene	ND	ND
Heptane	0.495	0.363
2,2-Dimethylhexane	ND	ND
Methylcyclohexane	0.325	0.158
2,5-Dimethylhexane	0.070	ND

Table A6

Burn Identification Monitoring Station I.D. Field Position	BOOM 4 BURN DW1B 14m, 197°N	BOOM 4 BURN DW2B 29m, 197°N
2,4-Dimethylhexane	0.085	ND
2,3,4-Trimethylpentane	ND	ND
Toluene	6.303	1.289
2-Methylheptane	0.214	0.134
1-Methylcyclohexene	ND	0.054
4-Methylheptane	ND	ND
3-Methylheptane	0.188	0.121
c-1,3-Dimethylcyclohexane	0.117	0.057
t-1,4-Dimethylcyclohexane	0.071	0.027
2,2,5-Trimethylhexane	ND	ND
1-Octene	0.311	ND
Octane	0.421	0.174
t-1,2-Dimethylcyclohexane	0.151	ND
c-1,4/t-1,3-Dimethylcyclohexane	0.061	ND
Ethylbenzene	0.744	0.200
m/p-Xylene	2.280	0.504
Styrene	0.437	0.049
o-Xylene	1.186	0.242
n-Nonane	0.874	0.186
iso-Propylbenzene	0.052	0.037
3,6-Dimethyloctane	0.210	ND
n-Propylbenzene	0.141	0.068
3-Ethyltoluene	0.327	0.116
4-Ethyltoluene	0.191	0.084
1,3,5-Trimethylbenzene	0.173	0.049
2-Ethyltoluene	0.163	0.065
1,2,4-Trimethylbenzene	0.688	0.185
Decane	1.581	0.215
iso-Butylbenzene	0.032	0.022
sec-Butylbenzene	0.034	0.027
1,2,3-Trimethylbenzene	0.236	0.059
p-Cymene	0.482	0.084
Indan	0.078	0.046
1,3-Diethylbenzene	0.052	0.038
1,4-Diethylbenzene	0.244	0.072
n-Butylbenzene	0.088	0.042
1,2-Diethylbenzene	0.035	0.028
Undecane	1.915	0.205
Naphthalene	0.401	0.119
Dodecane	2.217	0.222
Hexylbenzene	0.145	0.071

ND = Not Detected