

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, twelve 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 analyzers. Particulate samples in air were taken and analyzed for polycyclic aromatic hydrocarbons (PAHs). Water under the burns was analyzed; small amounts of PAHs were found. The burn residue was analyzed 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 (VOC) emissions were measured in Summa canisters. Over 100 compounds were identified and quantified; most concentrations were too low to be considered a health risk. It was concluded that small burns of this size (burn area about 25 m²) are too small to pose a health hazard.*

Introduction

In 1991, a series of mesoscale burn tests were initiated by a cooperative effort among several agencies. 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 in Mobile Bay, Alabama were used. Environment Canada (EC) and the U.S. Environmental Protection Agency (EPA) 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 crude oil burns and a large diesel burn was conducted in 1994. In 1997 and 1998, trials were conducted to

measure the performance of fire-resistant boom. This paper reports on the data from the 1998 trials involving diesel fuel. The U.S. Coast Guard and U.S. Minerals Management Service sponsored the burns and the boom tests for the purpose of testing fire-resistant containment booms. EC and the EPA sponsored the emission-measuring campaign.

Experimental

The primary goal of this series of test burns was the evaluation of six 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 conduct this project, a test tank was constructed on Little Sand Island. The tank had dimensions of 9.2 m (30 ft) width by 30.8 m (100 ft) length by 1.5 m (5 ft) depth.

During these burns, the Emergencies Science Division (ESD) of EC, in collaboration with the 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.

EC and EPA supplied a variety of ground-based instruments for sampling the air. In total, there were 16 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. Table 1 summarizes the test burns, and Table 2 gives the weather conditions prevalent during the tests.

Table 1. Basic experimental parameters.

Burn number	Boom number	Measurement number	Time (minutes)	Diesel amount (L)	Burn area (m ²)	Burn rate (mm/min)
1	1	1	48	2,517	14.3	3.7
1	1a	2	120	3,146		1.8
2	1a	3	42	1,575		2.6
3	1a	4	43	1,613		2.6
1	2	5	5	144	10.5	2.7
	Background	6	60			
2	2	7	34	878	11.8	2.5
1	3	8	62	2,514		3.4
2	3	9	59	2,514		3.6
3	3	10	63	2,514		3.4
1	4	11	71	3,751	17.0	3.1
2	4	12	63	3,308		4.4
3	4	13	61	3,308		4.6
	Background	14	60			
					Average	3.2

Table 2. Weather conditions during the burns.

	Mean wind speed (m/s)	Mean wind direction (°N)	Mean air temperature (°C)	Barometer (kPa)	Relative humidity (%)
Background (September 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

Note: Weather results in minimum < average < maximum format for the burn period. Wind sensors were 2 m high.

Detailed experimental procedures are given in Fingas *et al.* (2000). This paper provides a summary of basic procedures used. Water, fuel, and residue samples were collected directly, bottled, and preserved using standard methods and subsequently analyzed for PAHs and alkane distributions. Real-time particulate monitoring was conducted using the RAM and DataRAM (MIE Inc., Bedford, Massachusetts), commercially available pieces of equipment commonly used in the occupational health and safety industry. The omni-directional sampling head on the RAM is capable of measuring the total or 2–10 μm particulate fractions. The multiple values from the RAM were averaged over a period of 1 minute and recorded using a data logger. The DataRAM is an updated version of the RAM. The apparatus is capable of employing several different sampling head configurations: total particulate, the 0–10 μm particulate fractions or the 2.5 μm particulate fractions. The 10 μm fraction was used throughout the project. Total suspended particulates (TSPs) were measured using two different types of units: the high-volume air sampler commonly called TSP sampler (Andersen Graseby/GMW, Smyrna, Georgia) and the Model PS-1 PUF sampler (General Metal Works Inc., Cleves, Ohio). Total suspended particulates are classified as particles up to 25–50 μm size.

Two types of high-volume air sampling apparatus were employed in the 1998 trials to measure the PM₁₀ particulate fraction: the PM₁₀ sampler (Andersen Graseby/GMW, Smyrna, Georgia) and the ACFM nonviable ambient particle sizing sampler or more commonly, the Cascade Impactor system (Andersen Instruments Inc., Atlanta, Georgia). Three units were

deployed at the downwind 1A and 1B position and the upwind station. This is an 8-stage filter sampler in which each stage isolates an ever decreasing particulate fraction over the 2 to 10 μm range. A Partisol PM-2.5 sampler (Rupprecht & Patashnick, Albany, New York) was used to determine the amount of PM-2.5 sized matter in the air.

Carbon dioxide monitoring was performed using the Armstrong CD-1 (Armstrong Monitoring Corporation, Nepean, Ontario). Data were logged electronically. Carbonyls were sampled using an air pump to draw air through a DNPH (2,4 dinitrophenylhydrazine) silica cartridge (Millipore Corporation, Milford, Massachusetts).

To monitor the VOC concentration in air, an array of 6-L stainless steel Summa canisters were located at the monitoring stations. The canisters were pre-evacuated. The sampling orifices were opened and closed manually in coordination with the start and end of each burn. The Summa canisters used for VOCs also were used for carbon dioxide analysis.

The concentration of sulfur dioxide as the acid aerosol, sulphuric acid, in air was measured using the impinger method. The detection limit of the procedure was 0.25 ppm and all sample analysis showed results less than detection limit. The Zellweger/MDA Scientific Single Point Monitor (SPM) (Lincolnshire, Illinois) was also 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.

Table 3. Summary of particulate measurements.

	Station	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	1,156	1,247	1,263	975
	UW1B	16	110	4	64

Table 4. Correlation of measurements between samplers.

	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

Three portable environmental monitoring stations were set up at the experiment site to monitor local weather conditions. The stations simultaneously log wind speed, wind direction, temperature, barometric pressure, and relative humidity. Two of the stations were from Earth and Atmospheric Science, Inc. (Geneq Inc., Montreal, Quebec) and the third station was a WeatherPak system (Coastal Environmental, Seattle, Washington).

Results and discussion

Table 3 presents the same summary of all particulate measurements taken at the same location. The station location "UW" refers to the upwind station and the "DW" refers to downwind stations. 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.

The correlation among 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 a little smaller than the TSP values, as would be expected. The PM-2.5 values are about two-thirds 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.

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 phenanthrenes and dibenzo thiophenes is somewhat increased whereas the naphthalenes are reduced by the combustion. The amount of larger PAHs (e.g., benz(a)anthracene to benzo(ghi)perylene) are increased from a low concentration to a measurable concentration by combustion. The naphthalenes are reduced, phenanthrenes increased somewhat, the dibenzothiophenes reduced, fluorenes increased somewhat, and the chrysenes are increased significantly. The overall concentration of the alkylated PAHs is about the same in the starting diesel and the residue. It is important to recognize that because the residue constitutes a very small amount of the starting oil, that the fire largely destroys the PAHs. This is consistent with findings on previous diesel burns where the PAH distributions have been studied in detail (Wang *et al.*, 1998).

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

Table 8 shows the PAH concentrations on particulate filters. 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.

Table 5. Relationship of measurements between instrument readings.

Units	Ratio
TSP/PM-10 std.	1.2
TSP/PM-10 RAM	0.12
TSP/PM-2.5 std.	0.67
PM-10 S/PM-2.5	1.5

Table 6. PAH analysis of 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)
PAHs					
Naphthalene					
C0-N	0.273	0.021	0.04	89.1	311.7
C1-N	0.570	0.040	0.12	705.8	1,805.4
C2-N	0.339	0.039	1.22	2,258.9	4,255.5
C3-N	0.121	0.044	17.12	2,940.4	4,055.0
C4-N	0.048	0.040	42.13	1,825.6	1,830.6
Sum of naphthalenes	1.920	0.222	61	8,526	1,4064
Phenanthrene					
C0-P	0.027	0.016	0.25	601.3	270.3
C1-P	0.085	0.043	17.91	2,324.9	984.2
C2-P	0.121	0.057	103.84	2,957.7	1,123.8
C3-P	0.082	0.038	94.83	1,549.4	511.9
C4-P	0.061	0.028	64.88	901.4	226.2
Sum of phenanthrenes	0.377	0.182	282	8,335	3,116
Dibenzothiophene					
C0-D	0.002	0.002	0.30	352.0	602.0
C1-D	0.014	0.008	11.80	1,157.1	1,568.8
C2-D	0.018	0.011	62.18	1,591.6	1,688.5
C3-D	0.016	0.008	65.89	1,055.0	859.7
Sum of dibenzothiophenes	0.050	0.029	140	4,156	4,719
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	1,621.5	1,532.8
C3-F	0.035	0.026	67.59	1,516.9	1,213.1
Sum of fluorenes	0.097	0.067	111	4,285	3,874
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	25,572	25,827
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

Note: PAH, polycyclic aromatic hydrocarbon.

Table 7. n-Alkane distribution of water, diesel, and residue samples.

Sample type	Control (mg/kg water)	Pre-burn water (mg/kg water)	Post-burn water (mg/kg water)	Residue (mg/g oil)	Diesel (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
Total	0.0	0.0	5.8	138.1	193.8

Note: ND, not detected.

Table 9 summarizes the measurement of carbon dioxide using the Armstrong monitor. These correlate highly with the total concentrations measured in Summa canisters (Fingas *et al.*, 2000). 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 25 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.

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.

Sulphur dioxide measurements were taken both with the tapemeter instrument and an impinger that 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 most sulphur dioxide would be in an acid aerosol form not detectable by the instrument. The tapemeter did however record an average of 0.47 ppm of the acid form, H₂SO₄, 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.

Carbonyls were measured using an activated absorption tube. The carbonyls measured include aldehydes and some ketones.

Results from this measurement are presented in Table 10. 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.

VOCs were measured using multiple gas chromatographic techniques on samples taken from Summa canisters. One hundred forty-eight substances were analyzed. The results of these analyses are given in the literature (Fingas *et al.*, 2000). Table 11 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.

Summary and conclusions

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 µm³) only as far downwind as 30 to 75 m. This is related to burn area, which in this case was very small (~25 m²). 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

Table 8. PAH analysis results of particulate filters (µg/m³ 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
PAHs								
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 of naphthalenes	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 of phenanthrenes	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 of dibenzothiophenes	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 of fluorenes	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 of chrysenes	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

Note: CI, cascade impactor; PAH, polycyclic aromatic hydrocarbon.

Table 9. Carbon dioxide from the Armstrong CD-1 above instrument background.

	DW1A 16 m, 176°N	DW1B 14 m, 197°N	DW1C 16 m, 219°N	S1X 34 m, 132°N	S1Y 26 m, 151°N	UW1B 74 m, 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

Note: Results in minimum < average < maximum format in ppm.

Table 10. Carbonyl measurements (concentrations in µg/m³).

Compound	Boom 1 burn 1 + boom 1a burn 1 + 2 + 3		
	DW1B (1 m) 14 m, 197°N	DW2B (1 m) 29 m, 197°N	UW1B (1 m) 74 m, 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

Note: Data have been corrected with the average value of the instrument blanks and trip blank.

at the four sites where precision instruments were collocated. This may be indicative that the measurement devices break down soot particle.

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.

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, low and often just above detection limits. Overall, PAHs are still destroyed in the fire.

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 this size. In most cases, the levels were below the detection level of the equipment. One hundred 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.

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.

Overall, air emissions from small burns such as this are low and sometimes below the detection limits of the instruments and techniques to measure specific compounds. The emission of the

particulate material, the most toxic material to humans, is below health concern levels well within 500 m, often within 100 m.

Biography

Merv Fingas is Chief of the Emergencies Science Division in Environment Canada. Dr. Fingas' specialty is research in the analysis and behavior of oil spills in the environment. He manages 20 other scientists and staff studying various aspects of oil and chemical spills. He has devoted the last 27 years of his life to spill research and has over 450 papers and publications in the field.

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Table 11. 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