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LOCOMOTIVE FUEL EFFECTS STUDY: PARTICULATE SIZE CHARACTERIZATION

By

Steven G. Fritz
E. Robert Fanick

FINAL REPORT

Prepared for

CALIFORNIA AIR RESOURCES BOARD
STATIONARY SOURCE DIVISION - FUELS SECTION
P.O. BOX 2815
SACRAMENTO, CA 95814

JANUARY 2000

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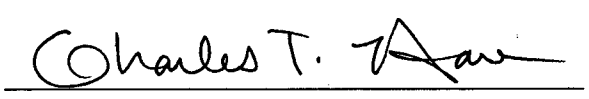

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FOREWORD

This project was performed for the California Air Resources Board (ARB) under SwRI Project 08-02062-003. The technical representative for ARB was Mr. Tony Brasil, Stationary Source Division - Fuels Section. The Principal Investigator was Mr. E. Robert Fanick, Senior Research Scientist, and the Project Manager for this work was Mr. Steven G. Fritz, Senior Research Engineer, both in the Department of Emissions Research. Mr. Michael J. Dammann, Group Leader in the Chemistry and Chemical Engineering Division, was responsible for the elemental analyses. SwRI technical personnel involved in engine operation, emissions sampling, and emissions analysis included Messrs. C. Eddie Grinstead, William L. Shackelford, and Ernesto San Miguel, all in the Department of Emissions Research. Ms. Yolanda Rodriguez and Ms. Kelley L. Strate performed the chemical analysis. Data reduction was performed by Ms. Kathleen M. Jack, Ms. Deborah A. Liston, and Ms. Sylvia G. Nino, also all in the Department of Emissions Research.

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LIST OF ABBREVIATIONS

AAR	Association of American Railroads
ARB	California Air Resources Board
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
BTU	British Thermal Unit
°C	degrees Centigrade
cc	cubic centimeter
CFR	Code of Federal Regulations
cSt	centistokes
DFI/GC™	direct filter injection, gas chromatography
EMD	Electro-Motive Division of General Motors Corporation
EP	end point
EPA	U.S. Environmental Protection Agency
°F	degrees Fahrenheit
FID	flame ionization detector
FTP	Federal Test Procedure
g	gram
gal	gallon
GE	Transportation Systems Division of the General Electric Company
H_2O	water
hp	horsepower
hr	hour
IBP	initial boiling point
IC	Ion Chromatography
ICP/MS	inductively-coupled plasma/mass spectroscopy
in	inch
L	liters
lb	pound
min	minute
mm	millimeter
MOUDI	micro-orifice uniform deposition impactor
NIST	National Institute of Standards and Technology
OEM	original equipment manufacturer
PM	particulate matter
ppm	parts per million
sec	seconds
SOF	soluble organic fraction
SwRI	Southwest Research Institute
UP	Union Pacific Railroad
VOF	volatile organic fraction
wt	weight
%	percent
Fm	micrometer (1×10^{-6} meter), micron

EXECUTIVE SUMMARY

This report documents results from exhaust particulate size distribution measurements performed on a 4,400 hp General Electric model DASH9-44CW diesel locomotive engine. This locomotive (UP No. 9724) was one of six locomotives tested for the California Air Resources Board (ARB) as part of a fuel effects study.

For the particulate size determination work reported herein, two fuels were compared; CARB diesel and a nonroad diesel fuel with a fuel sulfur level of 0.3 percent (3,190 ppm). These fuels were two of the four fuels used in the ARB locomotive fuel effects study. Tests were run at only two operating conditions: Idle and Notch 8 (rated power). Particle size distribution was measured using a Model 110 micro-orifice uniform deposit impactor (MOUDI). Additional analysis of the size-segregated particulate included determination of the volatile organic fraction (VOF), elemental analysis, and anion and cation analyses.

Less than one percent of the particulate for both fuels was larger than 2.5 Fm ($PM_{2.5}$), at both Idle and Notch 8. As expected, the total particulate mass rate was higher with the 0.3 percent sulfur nonroad diesel fuel at both operating conditions. One significant finding of this study was that the PM mass emission rates were similar for both fuels down to a particle size of 0.17 Fm. Most of the difference in total PM observed between the two fuels occurred in the smaller size ranges, 0.17 Fm to 0.09 Fm, 0.09 Fm to 0.056 Fm, and less than 0.056 Fm, where the 0.3 percent sulfur fuel had significantly higher mass emission rates. Subsequent analysis of the PM samples showed that the increased PM at the smaller size fractions was largely attributed to fuel-derived portion of the VOF and to sulfate emissions. Another interesting finding from this study was that for both fuels, the particle size distribution at Idle was monomodal, and at Notch 8 it was bimodal.

An elemental analysis was performed on selected size ranges, and only five elements detectable by XRF were present in enough quantity to be above detection limits. These elements were barium, manganese, nickel, sulfur, and zinc. The various metal elements were mostly attributed to engine wear metals, and the sulfur came from the fuel and lubricating oil. Except for sulfur, the metal elements contributed only a small fraction to the total particulate mass. At both Idle and Notch 8, most elements detected were in the 0.54 Fm to 0.31 Fm, 0.31 Fm to 0.17 Fm, and 0.17 Fm to 0.09 Fm particle size ranges.

For the anions and cations analyzed, sulfate was detected at the highest mass emission rates, especially with the higher sulfur fuel. Chloride, nitrate, and potassium ions were detected, but contributed only a small fraction to the total particulate mass.

I. INTRODUCTION AND BACKGROUND

This project was an experimental program intended to characterize the size distribution of exhaust particles from a locomotive engine. Particulate characterization by particle size included the volatile organic carbon content, elemental analysis, and anion and cation mass emission rates. The work was performed to determine the particulate composition and how the particulate characteristics change in relation to the size of particle. Exhaust emission and fuel consumption measurements were performed using a 4,400 hp, General Electric (GE), model DASH9-44CW locomotive, provide by Union Pacific Railroad (UP).

The EPA definition of an engine exhaust particulate is any material collected on a fluorocarbon-coated glass fiber or fluorocarbon-based (membrane) filter, from a dilute exhaust stream, at a sample zone temperature less than 52EC (125EF). For particulate measurement, the engine's raw exhaust is typically diluted in a tunnel, which is generally about 8 to 18 inches in diameter and about 20 feet long. The dilution ratio generally ranges from 2:1 to 20:1, depending on engine operating conditions, tunnel air flow capacity, and system control characteristics required to meet the sample zone temperature requirements. For a given engine, the number and size of particles in the exhaust are functions of many variables including the sample probe location in the plume. The predominant size range in terms of total mass is larger than 0.1 micron, and in terms of number of particles, the predominant size is below 0.1 micron. The dependence of particle size and number on sample probe location is directly related to the temperature, dilution, and "age" of the particles. As engine exhaust cools, the higher molecular weight gaseous hydrocarbons begin to condense into aerosols, the particles tend to agglomerate, and adsorption of hydrocarbons may occur. Each mechanism results in larger and heavier particles.

In this study, the aerodynamic diameter is defined as the diameter of a unit density sphere (1 g/cc) having the same settling speed in air as the measured particle. Sizing devices such as cascade impactors use aerodynamic principles to size particles. In an impactor, a sample containing particles with a mixture of shapes and densities is fractionated and collected according to aerodynamic characteristics. As the sample stream passes through stages in the impactor with apertures of decreasing width or diameter, flow is accelerated and progressively smaller particles collect on impaction plates. Particles which are aerodynamically equivalent in size to the unit density spheres are collected on specific stages, calibrated under similar conditions. The mass collected on each stage indicates the percentage of particles within a specific aerodynamic diameter range.

II. TECHNICAL APPROACH

Testing was performed at the Southwest Research Institute (SwRI) Locomotive Exhaust Emissions Test Center in San Antonio, Texas. This unique facility was established in 1993 in cooperation with the Association of American Railroads (AAR), and is the only non-original equipment manufacturer (non-OEM) facility capable of performing locomotive exhaust emission tests.

Presented below is an overview of the technical approach used to conduct locomotive exhaust emissions testing for this study. A description of the locomotive selected for testing, engine power measurement, fuel consumption measurement, the test fuels used in this program, exhaust emissions test procedures, and particulate measurement procedures are also included. Analytical procedures for particulate characterization are included in Section III of this report.

A. Test Locomotive

Exhaust particulate size distribution measurements were performed on a General Electric (GE) model DASH9-44CW diesel locomotive engine. This locomotive, UP No. 9724, was one of six locomotives tested for the California Air Resources Board (ARB) as part of a fuel effects study. UP No. 9724 was manufactured in July 1994, and has the serial number 47870. It was equipped with a 4,400 hp, GE model 7FDL16N62, turbocharged diesel engine (SN 970815R), which was remanufactured by GE in August 1997.

B. Engine Power Measurement

Most line-haul locomotives are equipped with the "dynamic brake" feature in which the electric motors used for traction are reverse-excited to become generators to slow the train. The electrical power generated is dissipated in resistance grids. Those locomotives with the self-load feature can dissipate the main alternator power into these "dynamic brake" resistance grids. UP. No. 9724 was equipped with resistance load grids that were capable of loading the engine to its full power level of 4,400 hp.

The goal of power measurements was to compute the net engine power produced to perform work, referred to as flywheel or “gross” power. Gross power for the GE locomotive was recorded from the on-board computer display. Gross power represents the sum of “traction power” plus “auxiliary power.”

C. Fuel Consumption Measurement

Diesel fuel consumption rate was measured on a mass basis, using a mass flow meter adapted from laboratory use at SwRI. The system was equipped with a heat exchanger to control fuel supply temperature to 90±10°F. Hot return fuel from the engine that normally returns to the locomotive fuel tank was cooled before returning to the fuel measurement reservoir ("day" tank) to assure consistent fuel supply temperature to the engine.

D. Test Fuels

Two fuels were used for this particulate characterization study. The first fuel was a 0.3 percent sulfur nonroad diesel fuel, with an aromatic level of about 40 percent and a cetane number of 44.5. The second fuel was a blend of two commercially available CARB diesel fuels with a sulfur level of 50 ppm (0.005 percent) and an aromatic content of 22 percent by volume. This fuel consisted of 8,000 gallons of commercially available CARB-approved diesel fuel from the Texaco refinery in Los Angeles, California plus another 8,000 gallons of commercially-available CARB-approved diesel fuel from the ARCO refinery in South Gate, California. Each fuel was delivered to the SwRI Locomotive Exhaust Emissions Test Center by truck and the fuels were mixed in a single railroad tank car. Table 1 gives selected properties for the two fuels. Table 2 gives the results of a metals analysis of the two fuels.

E. Regulated Exhaust Emissions Test Procedure

SwRI used the Federal Test Procedure (FTP) for locomotives as detailed in 40 CFR Part 92, Subpart B as the basis for emission measurement techniques. For this study, two throttle notch settings were used: Idle and Notch 8.

Particulate emissions were measured at each test point using a "split then dilute" technique, in which a portion of the raw locomotive exhaust was “split” off of the total flow and mixed with filtered air in a 10-inch diameter dilution tunnel. The split sample was transferred to the dilution tunnel through a 2-inch diameter stainless steel tube that was insulated and electrically heated to 375°F. This dilution tunnel was located at ground level, next to the locomotive, as shown in Figure 1. Particulate samples from the dilute exhaust were collected using an isokinetic sampling probe shown in Figure 2.

Before emission testing was started, the engine was first brought to operating temperature. This procedure involved operating the locomotive at Notch 8 for at least 15 minutes. After the warm-up period, testing began with Idle using the 0.3 percent sulfur fuel. Four consecutive repeat tests were performed to collect sufficient samples for the various analytical procedures. The engine was then brought to Notch 8, and the sequence of four consecutive tests was repeated. After a fuel change to the CARB diesel, the sampling sequence was repeated at Idle and Notch 8.

TABLE 1. SELECTED PROPERTIES OF THE TWO LOCOMOTIVE TEST FUELS

Determinations	ASTM Test Method	CARB Diesel EM-2663-F	0.3% Sulfur Nonroad Diesel EM-2708-F	EPA Locomotive Spec. [a]
API Gravity @ 60°F	D4052	39.1	34.1	32 - 37
specific gravity		0.8295	0.8547	ns
density (lb/gal)		6.92	7.13	ns
Viscosity @ 40EC (cSt)	D445-83	2.46	2.77	2.0 - 3.2
Sulfur (Wt%)	D2622-94	0.005	0.319	0.2 - 0.4
Cetane Index	D976	52.0	46.5	40 - 48
Cetane Index	D4737	53.1	46.6	ns
Cetane Number	D613-84	51.0	44.5	40 - 48
Nitrogen Content (ppm)	D4629-96	8.4	220.1	ns
Heat of Combustion	D240			
Gross (BTU/lb)		19,715	19,440	ns
Net (BTU/lb)		18,479	18,240	ns
Gross (BTU/gal)		136,400	138,600	ns
Net (btu/gal)		127,900	130,100	ns
Carbon-Hydrogen Ratio	D3178			
% Carbon		86.37	86.77	ns
% Hydrogen		13.63	13.23	ns
Hydrogen/Carbon Ratio		1.880	1.818	ns
SFC Aromatics	D5186-96			
Total Mass %		22.39	33.11	27 min.
PNA Mass %		1.66	8.89	
Hydrocarbon Type	D1319-84			
Aromatics (%)		22.4	39.8	ns
Olefins (%)		2.0	2.5	ns
Saturates (%)		75.6	57.7	ns
Flash Point (°F)	D93-80	167	166	130 min.
Distillation	D86-96			
	% Recovered	Temp. °F	Temp. °F	Temp. °F
	IBP	368	375	340 - 400
	10	413	426	400 - 460
	50	490	513	470 - 540
	90	606	620	560 - 630
	EP	659	672	610 - 690

Note: a - Diesel fuel for locomotive testing as specified by EPA in 40 CFR 92, §92.113, Table B113-1.
ns - not specified

TABLE 2. TEST FUEL METALS ANALYSIS RESULTS

Element	ASTM Test Method	CARB Diesel EM-2663-F	0.3% Sulfur Nonroad Diesel EM-2708-F
Fuel Metals Analysis			
Antimony, ppm	D5185	<1	<1
Arsenic, ppm		<5	<5
Beryllium, ppm		<2.5	<5
Cadmium, ppm		<1	<1
Chromium, ppm		<1	<1
Cobalt, ppm		<2.5	<5
Copper, ppm		<1	<1
Lead, ppm		<1	1
Manganese, ppm		<1	<1
Mercury, ppm		<5	<5
Nickel, ppm		<1	<1
Selenium, ppm		<5	<5

FIGURE 1. EMISSIONS TEST SETUP USED FOR SAMPLING PARTICULATE

FIGURE 2. ISOKINETIC PARTICULATE SAMPLE PROBE USED WITHIN DILUTION TUNNEL FOR PARTICLE SIZING MEASUREMENTS

III. DESCRIPTION OF ANALYTICAL METHODS

This section of the report describes the analytical methods used for assessing particle size distribution of particulate emissions, and the subsequent chemical characterization of the particulate collected.

A. MOUDI for Particle Size Distribution

Particle size distribution was measured using a Model 110 micro-orifice uniform deposit impactor (MOUDI) with an isokinetic sampling probe located within the dilution tunnel. The sample flow rate through the MOUDI was 30 L/min. Nine MOUDI stages were used to collect particulate having particle diameter cut-off of ranges of greater than 6.2 Fm, 3.1 to 6.2 Fm, 1.8 to 3.1 Fm, 1.0 to 1.8 Fm, 0.54 to 1.0 Fm, 0.31 to 0.54 Fm, 0.17 to 0.31 Fm, 0.09 to 0.17 Fm, and 0.056 to 0.09 Fm. The last stage was followed by a 47 mm Pallflex T60A20 backup filter to collect particles below 0.056 Fm. Figure 3 shows the MOUDI installed at the locomotive test center.

FIGURE 3. MOUDI PARTICLE SIZE SYSTEM USED AT LOCOMOTIVE TEST CENTER

The MOUDI operating principal is the same as any inertial cascade impactor with multiple nozzles. At each stage, jets of particle-laden dilute exhaust impinge upon an impaction plate. Particles larger than the mean diameter cut-size of that stage have inertia sufficient to cross the air streamlines to impact the plate. Upon contact with the plate, the particles remain on the impaction plate. Smaller particles have less inertia, cannot cross the streamlines, and proceed to the next stage. Smaller nozzles, with higher air velocity, are used to separate finer particles. The process continues through the cascade impactor until particles smaller than the last stage collection capability are collected on the final glass fiber backup filter. By rotating every other stage of the impactor and holding the others stationary, every nozzle plate rotates relative to its impaction plate. This relative rotation allows the MOUDI to achieve near uniform particle deposition on the impaction plates. Figure 4 shows particulate collected on one of the impaction plates of a MOUDI stage.

FIGURE 4. PARTICULATE COLLECTED ON ONE OF THE IMPACTION PLATES OF A MOUDI STAGE

For gravimetric particle size distribution and for the volatile organic fraction (VOF) determinations, uncoated aluminum foil plates were used to collect samples. These foils are the typical collection media used for the MOUDI system. Nucleopore substrates were used in place of the aluminum foil plates to collect samples for subsequent characterization of metals, cations, and anions. In all, four runs at each operating condition were performed. Run 1 used standard uncoated 47-mm aluminum foil plates to accumulate particulate. These filters were used for gravimetric mass determination. Run 2 also used uncoated 47-mm aluminum foil

plates. These plates were used to replicate data for gravimetric mass determination, and were then used to determine the volatile organic fraction (VOF) of the collected particulate. Run 3 used 47-mm Nucleopore filter media as plates, in place of the conventional aluminum foils. These filters were used for subsequent elemental analysis, as described below in Section III.C. Run 4 used a second set of 47-mm Nucleopore filter media. These filters were used for subsequent analysis for anions and cations, as described below in Section III.D.

B. DFI/GC for VOF

Direct filter injection gas chromatography (DFI/GC) was used to determine the VOF of the particulate at selected size fractions. VOF is defined in this study as organic material that responds on a flame ionization detector (FID), and has a boiling point of less than approximately 600EF. In addition, the contribution of unburned lubricating oil to VOF was also determined by an interpretive procedure based on simulated distillation boiling point distribution of a lubricating oil sample from the locomotive. The difference between the unburned oil derived VOF and the total VOF is a combination of unburned fuel, oxidized lubricating oil, and oxidized fuel components with a lower boiling temperature than the lubricating oil. For this study, the combination of these lower boiling components will be defined as “fuel-derived VOF”.

Direct DFI/GC processing of the aluminum foil plates was not possible, so the material collected on each foil was transferred to 47-mm Pallflex T60A20 particulate filters for analysis. Lubricating oil from the locomotive was used to quantify the boiling point distribution of unburned lubricating oil contribution to the VOF.

VOF analyses were conducted using a Perkin Elmer Model 8500 gas chromatograph (GC) equipped with a uniquely designed filter injection system and a FID. Pallflex filters containing the samples transferred from the foils were placed into the injector, which was subsequently inserted into a cool zone of the DFI/GC to allow any oxygen in the system to be purged without losing any sample by desorption. When all oxygen had been purged from the system, the injector was pushed into a hot zone of the GC, where the volatile materials were desorbed and deposited into a cool column. A GC temperature program was then used to separate the volatilized compounds by boiling point. These compounds were then detected with a FID.

C. ICP/MS for Elemental Analysis

An inductively coupled plasma, mass spectroscopy (ICP/MS) method was used for determining the elemental content of particulate collected on selected MOUDI plates. Nucleopore filters or plates from individual stages were digested in a mixture of nitric and perchloric acid, followed by digestion with aqua regia. The resulting solution was analyzed by ICP/MS for the elements given in Table 3.

TABLE 3. ELEMENTS STUDIES BY ICP/MS

Aluminum - Al	Antimony - Sb	Arsenic - As
Barium - Ba	Beryllium - Be	Bismuth - Bi
Boron - B	Cadmium - Cd	Calcium - Ca
Chromium - Cr	Cobalt - Co	Copper - Cu
Galium - Ga	Gold - Au	Indium - In
Iron - Fe	Lanthanum - La	Lead - Pb
Lithium - Li	Magnesium - Mg	Manganese - Mn
Mercury - Hg	Molybdenum - Mo	Nickel - Ni
Palladium - Pd	Phosphorus - P	Potassium - K
Ruthenium - Ru	Selenium - Se	Silicon - Si
Silver - Ag	Sodium - Na	Strontium - Sr
Yttrium - Y	Thallium - Tl	Thorium - Th
Tin - Sn	Titanium - Ti	Tungsten - W
Uranium - U	Vanadium - V	Zinc - Zn
Zirconium - Zr		

The ICP/MS instrument was standardized using reference materials that were traceable to the National Institute of Standards and Technology (NIST). Prior to the analysis of any samples, the standardization was also verified with a second NIST traceable reference material. This second standard was from a different lot or manufacturer than the standardization material, and served as a check sample. Immediately after a check sample was run, a blank sample was also run to verify the zero setting of the standardization. The check sample was required to be within the control limits of 90-110 percent recovery of the certified value. The absolute value of the check blank was required to be below the reporting limit for the samples. If either condition was not met, the analysis was terminated and the instrument re-standardized and re-checked. The check sample and check blank were re-run after every ten samples and at the end of the run to ensure that the instrument remained in control throughout the entire run of ten samples. The same control limits were used for the continuing check samples. If a continuing check sample fell out of the control limits, the analysis was terminated, the instrument re-standardized, and all samples processed since the

last compliant check sample were re-run. Detection limits were on the order of 1 to 5 Fg/filter for most elements.

D. IC for Anions and Cations

Anions and cations accumulated on each Nucleopore filter impactor plate were quantified using an ion chromotography (IC) process, where selected stages were extracted by shaking each Nucleopore filter in a solution of 60 percent isopropanol (IPA) and 40 percent water. Analyses of the extracted anions and cations were conducted using an IC equipped with a conductivity detector.

1. Anions -- Sulfate, Nitrate, and Chloride Ions

Sulfuric acid on the filter was converted to ammonium sulfate by exposure to ammonia vapor in a conditioning chamber. The soluble sulfates and other anions were then leached from the filter with a measured volume of 60 percent IPA and 40 percent water. An aliquot of this extract was injected via autosampler into an IC. Anions were separated by analytical column with a dilute solution of sodium bicarbonate and sodium carbonate as the eluent, and then passed through a conductivity detector. The retention time on column provide identification of the anions, with the intensity of the signal corresponding to the concentration of the anion detected.

2. Cations -- Ammonium and Potassium Ions

Cations were analyzed in a similar manner as the anions except the eluent was nitric acid. The soluble cations were leached from the Nucleopore filter with a measured volume of 60 percent IPA and 40 percent water. An aliquot of this extract was injected via autosampler into an IC. Cations were separated by analytical column, and passed through a conductivity detector. The retention time on column provided identification of the cations, with intensity of the signal corresponding to the cation concentration.

IV. TEST RESULTS

A. Particle Size Distribution

Table 4 summarizes the results of the GE locomotive particle size distribution at Idle and Notch 8 for both fuels. Given are particulate matter (PM) mass emission rates in ten discrete particle size ranges, and a total particulate mass rate, which is the sum of all the stage fractions collected plus the backup filter.

As described in Section III.A of this report, duplicate tests were performed using the standard foil media and Nucleopore media in the MOUDI at each of the two operating conditions, and for each of the two test fuels. The data in Table 4 shows that the particle size distribution obtained with the foil plates and the Nucleopore media as an impaction plate yielded similar results, although the sum of the stage values (the total PM emission rate) was consistently higher when using the Nucleopore media compared to the foil plates. Table 4 also contains the PM rate for each test condition and fuel that is based on conventional PM sampling techniques using 90mm Pallflex T60A20 filter media. The value reported as "Total PM by 90mm" is the average of triplicate tests reported to the ARB as part of the main test program on this locomotive. Comparing the 90mm PM results to the PM totals by the MOUDI show that the Nucleopore media seemed to agree better than the foils, with the possible exception of the first Notch 8 run with the 0.3 percent sulfur fuel, where the total PM by MOUDI was almost twice as high as the 90 mm PM. Comparing the PM totals by MOUDI using foil plates are often compared against total PM measured with conventional sampling systems, and MOUDI total PM values are typically in the range of 60 to 90 percent of those measured by conventional 90mm filters. In this case, the Nucleopore filters used as impaction plates seemed to collect more mass at each stage compared to the foil plates, although the size distributions were similar. Due to the fact that the foil plates are the collection media typically used in MOUDI sampling, the following discussion of particle size is based on data using the foils.

The duplicate runs using the foil media were averaged, and the results are presented in Figure 5, in percentages of total PM mass as a function of particle size. At Idle, for both fuels, about 1 percent of the total PM mass was from particles larger than 2.5 Fm. At Notch 8, less than 1 percent of the total PM mass was from particles larger than 2.5 Fm, for both fuels. Figure 5 also shows that the 0.3 percent sulfur fuel had a larger percentage of smaller particles than the CARB diesel, at both Idle and Notch 8. Also, there was a larger fraction of smaller particles at Notch 8 than at Idle.

Figure 6 shows the particulate mass emission rate during Idle operation as a function of particle size, based on the aluminum foil collection plates. Both fuels exhibited a monomodal distribution, with the largest mass fraction at the 0.31 to 0.54 Fm size range. The PM mass emission rate was higher with the 0.3 percent sulfur fuel at all size ranges except at the 0.17 to 0.31Fm size range.

TABLE 4. GE LOCOMOTIVE ENGINE PARTICULATE EMISSION SIZE DISTRIBUTION SUMMARY

	0.3% Sulfur Nonroad Diesel				CARB Diesel			
Low Idle PM Emissions, g/hr								
PM Size Range, Fm	Foil Run 1	Foil Run 2	Nucleopore Run 1	Nucleopore Run 2	Foil Run 1	Foil Run 2	Nucleopore Run 1	Nucleopore Run 2
> 6.2	0.00	0.00	2.71	2.76	0.00	0.08	1.35	0.72
3.1 to 6.2	0.36	0.36	2.44	2.21	0.00	0.11	1.04	0.62
1.8 to 3.1	0.41	1.61	3.61	1.98	0.00	0.00	1.31	0.57
1.0 to 1.8	0.41	1.52	1.35	3.22	0.24	0.00	1.70	1.13
0.54 to 1.0	0.68	2.50	5.33	3.54	0.93	0.49	2.08	1.75
0.31 to 0.54	11.34	14.42	11.42	11.77	12.23	9.86	12.56	13.15
0.17 to 0.31	8.45	8.57	13.68	13.52	11.79	6.81	14.26	12.17
0.09 to 0.17	4.70	7.95	9.03	10.12	2.37	1.39	3.74	3.56
0.06 to 0.09	2.21	2.37	4.74	4.14	0.84	0.56	2.27	1.96
< 0.06	1.76	3.04	2.21	1.52	0.76	0.45	0.92	0.77
Total PM by MOUDI	**30.32**	**42.32**	**53.81**	**52.02**	**29.17**	**19.68**	**39.88**	**35.68**
Total PM by 90 mm [a]	**58**				**48**			
Notch 8 PM Emissions, g/hr								
> 6.2	6.43	2.77	47.76	25.12	3.07	0.00	0.00	24.71
3.1 to 6.2	0.00	0.00	95.51	19.53	0.00	0.00	21.54	12.35
1.8 to 3.1	2.57	0.00	78.06	17.67	2.30	0.00	15.38	27.02
1.0 to 1.8	0.00	2.77	110.21	32.56	0.00	1.58	23.08	27.79
0.54 to 1.0	3.86	3.70	138.68	60.46	4.60	0.00	19.23	23.93
0.31 to 0.54	69.44	92.47	175.41	143.25	76.67	76.78	86.92	101.14
0.17 to 0.31	39.86	58.25	177.25	85.58	45.24	40.37	66.15	66.40
0.09 to 0.17	115.74	115.58	195.62	156.28	69.00	44.33	76.15	54.04
0.06 to 0.09	102.88	114.66	117.55	141.39	68.24	51.45	79.23	57.90
< 0.06	61.73	54.55	59.70	48.37	30.67	29.29	30.00	36.29
Total PM by MOUDI	**396.07**	**441.99**	**1147.99**	**705.11**	**296.71**	**243.81**	**417.68**	**406.87**
Total PM by 90 mm [a]	**646**				**409**			

Notes: a - Total PM by 90 mm is the average of the triplicate runs made during regulated emissions testing of UP No. 9724, as measured using 90mm Pallflex T60A20 filters.

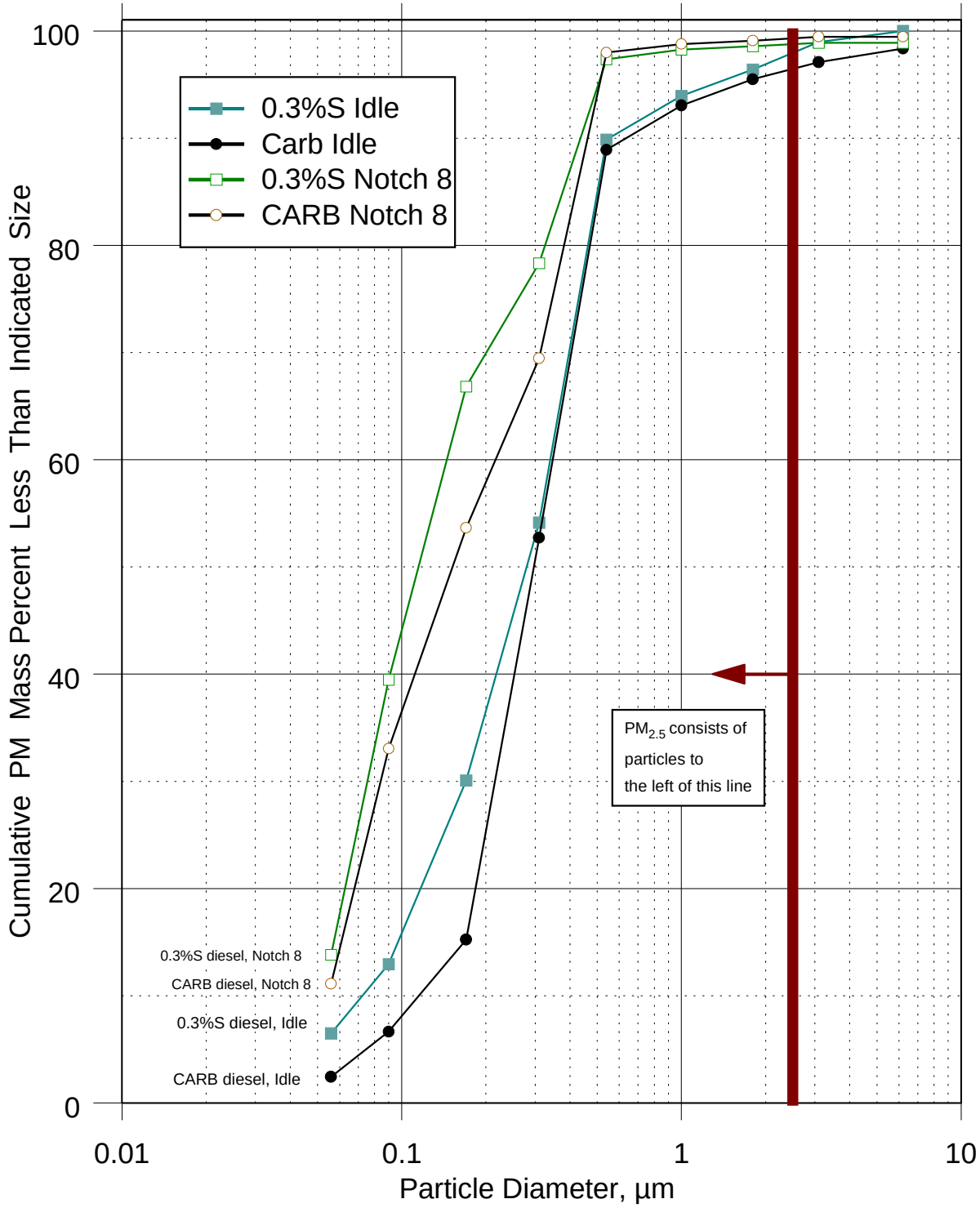

FIGURE 5. GE LOCOMOTIVE ENGINE PARTICLE SIZE DISTRIBUTION

Figure 7 shows the particulate mass emission rate during Notch 8 operation as a function of particle size, based on the aluminum foil collection plates. Comparing Idle to Notch 8, there is a noticeable shift in the particle size distribution toward smaller particles, and the total mass emission rate is about an order of magnitude higher. At Notch 8, less than 3 percent of the particulate mass emission was above 0.54 Fm for both fuels. An interesting characteristic of the size distribution at Notch 8 is that it was bimodal for both fuels, with one peak at 0.31 to 0.54 Fm size range, like that observed at Idle, but with a second peak around the 0.09 to 0.17Fm size range. It is at this peak in the smaller particle size range where the greatest difference in PM emissions between the two fuels was observed, with PM mass emissions with the 0.3 percent sulfur fuel nearly twice as high as the CARB diesel in the three size ranges below 0.17 Fm.

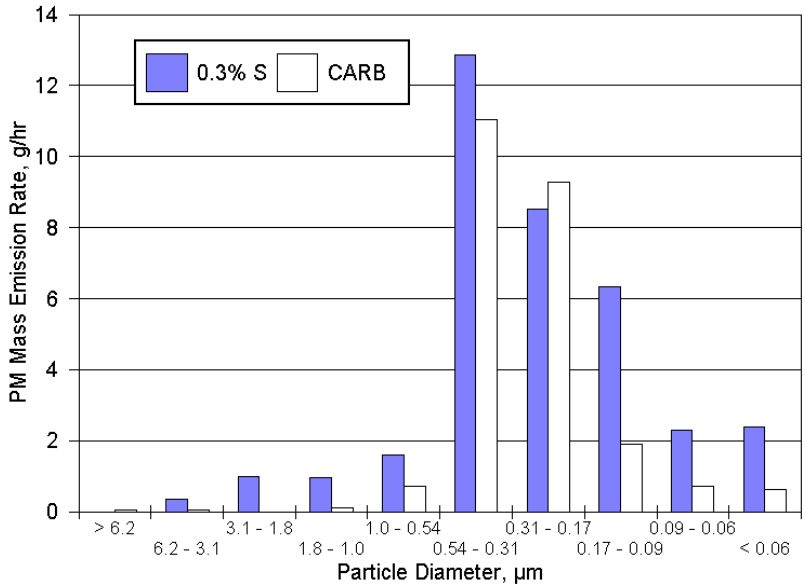

FIGURE 6. PARTICLE SIZE DISTRIBUTION AT IDLE

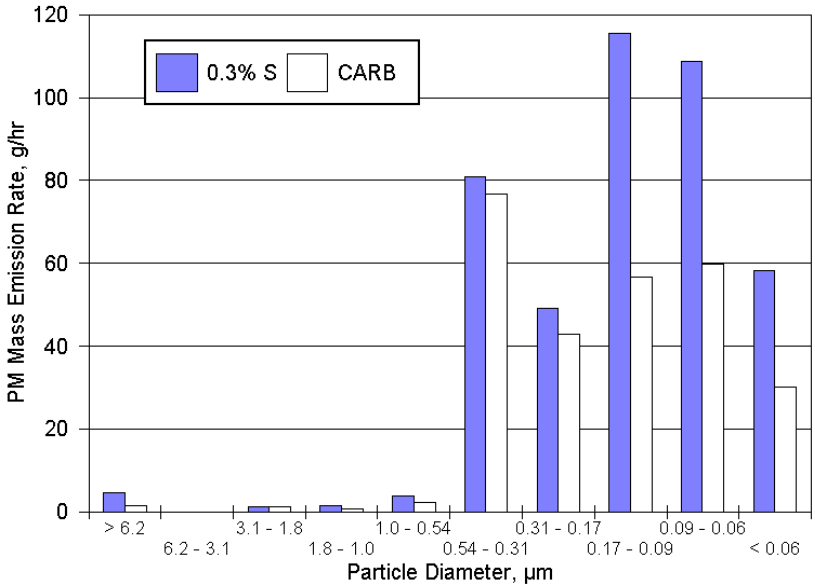

FIGURE 7. PARTICLE SIZE DISTRIBUTION AT NOTCH 8

B. Volatile Organic Fraction (VOF) of Particulate

Stages with mean diameter ranges of 0.54 Fm to 0.31 Fm, 0.31 Fm to 0.17 Fm, and 0.17 Fm to 0.09 Fm for Idle were analyzed by DFI/GC for VOF. At Notch 8, the same three stages used in Idle VOF analysis, plus the 0.09 Fm to 0.056 Fm stage, and the less than 0.056 Fm backup filter were examined. Particulate mass loadings for the other stages were too small to permit particulate characterization by VOF. The DFI/GC procedure provides a result based on the percentage of total PM that is VOF. In this case, the percentage of the PM was measured using the MOUDI foil plates. The percent VOF determined for each stage was applied to the average PM emission of the two runs made with the foil plates at each test condition. The VOF results are presented in Table 5, and in Figures 8 and 9.

TABLE 5. VOLATILE ORGANIC FRACTION (VOF) OF PARTICULATE

Engine Condition	Fuel	Average Total Particulate, g/hr	Size Range, Fm	% VOF	VOF, g/hr	% Unburned Oil of VOF	Unburned Oil, g/hr	Fuel-Derived VOF, g/hr
Idle	0.3% Sulfur	36	0.54-0.31	9.2	3.9	32	1.3	2.6
			0.31-0.17	7.3	3.1	21	0.7	2.4
			0.17-0.09	3.6	1.5	4	0.1	1.4
	CARB Diesel	24	0.54-0.31	4.9	1.0	40	0.4	0.6
			0.31-0.17	6.8	1.3	18	0.2	1.1
			0.17-0.09	4.0	0.8	6	0.04	0.8
Notch 8	0.3% Sulfur	419	0.54-0.31	6.3	27.7	15	4.2	23.5
			0.31-0.17	8.3	36.0	9	3.2	32.8
			0.17-0.09	10.5	45.9	15	6.9	39.0
			0.09-0.056	5.5	23.9	4	1.0	22.9
			<0.056	8.1	35.2	29	10.2	25.0
	CARB Diesel	270	0.54-0.31	7.0	17.1	22	3.8	13.3
			0.31-0.17	9.1	22.0	21	4.6	17.4
			0.17-0.09	7.4	17.9	25	4.5	13.4
			0.09-0.056	6.0	14.5	12	1.7	12.8
			<0.056	8.2	20.1	42	8.4	11.7

The data given in Table 5 shows that the VOF of the PM emissions from the GE engine is relatively low, and makes up only 5 to 10 percent of the total PM mass. Figures 8 and 9 show that the VOF is largely fuel-derived, at both Idle and Notch 8. The mass rate of unburned lubricating oil-derived VOF was generally similar for both fuels, especially during Notch 8 operation. At Idle, the lubricating oil derived VOF was higher with the 0.3 percent sulfur diesel fuel, compared to the CARB diesel, with notable increases observed at the two larger size ranges analyzed. At Notch 8, the largest contribution to the VOF from unburned lubricating oil was at the smallest size range analyzed, which was less than 0.056 Fm.

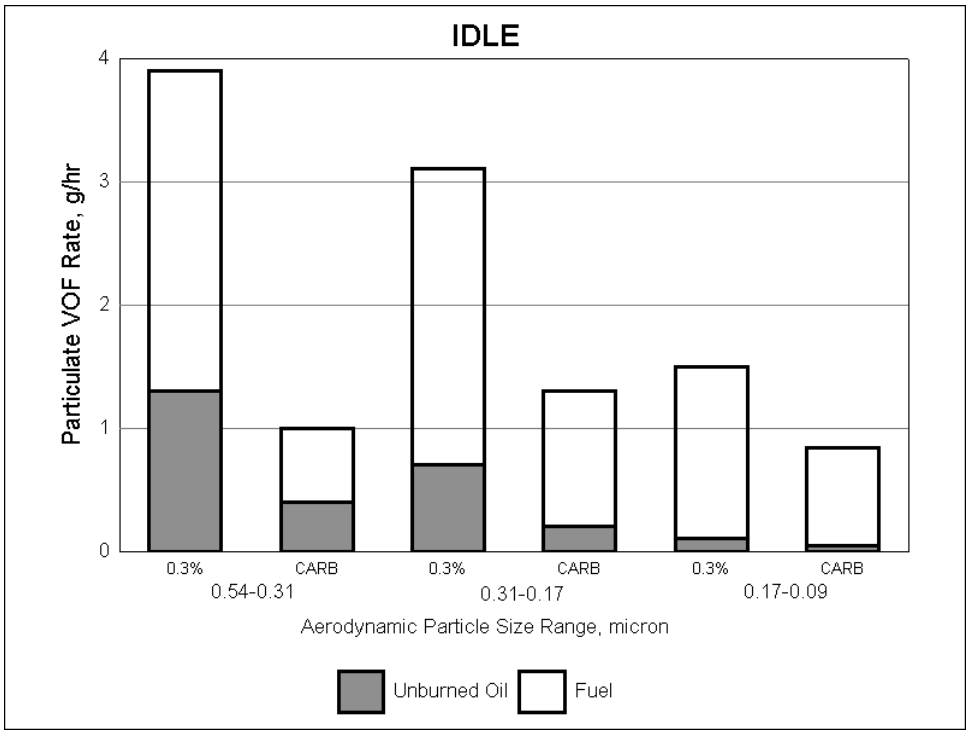

FIGURE 8. VOF AT IDLE

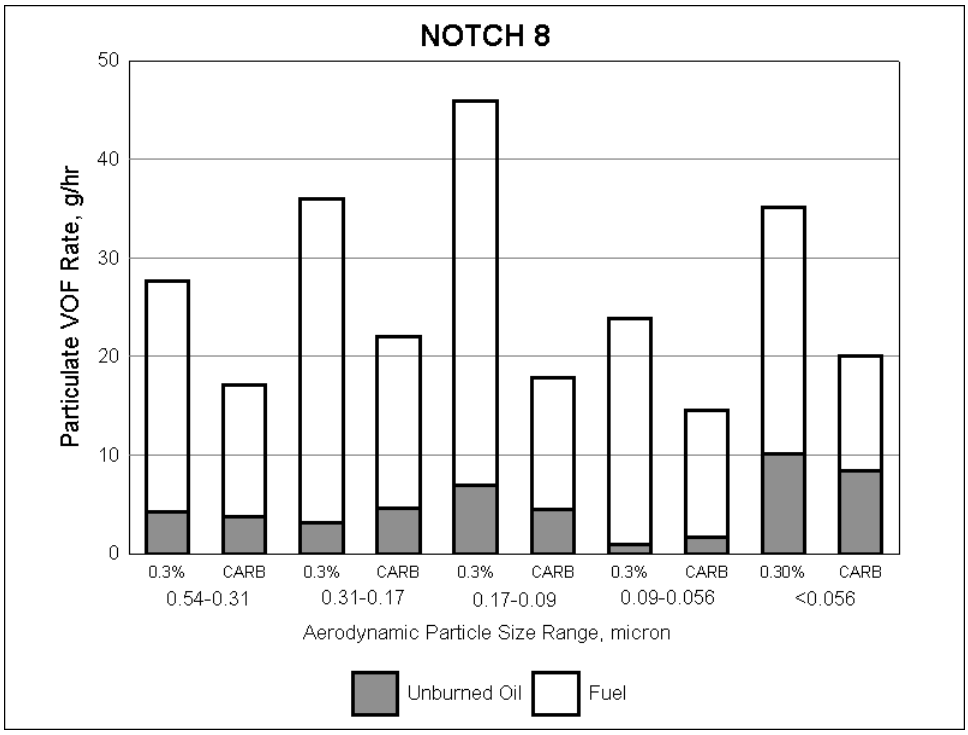

FIGURE 9. VOF AT NOTCH 8

C. Elemental Analysis

MOUDI stages using Nucleopore filters and with particle sizes of 0.54 Fm to 0.31 Fm, 0.31 Fm to 0.17 Fm, and 0.17 Fm to 0.09 Fm for Idle were analyzed by ICP/MS for selected elements. At Notch 8, the same stages, plus the 0.09 Fm to 0.056 Fm stage, and the less than 0.056 Fm backup filter were examined. Particulate mass loadings for the other stages were too low to permit particle characterization. A total of 44 elements were analyzed for, but most were below their detection limit.

Appendix A gives the tabulated results of the elemental analysis on selected MOUDI stages. Only four elements (barium, magnesium, potassium, and sulfur) were above the detection limit for the stages analyzed, and only sulfur was found repeatedly. Several elements were found at trace levels, defined as being present above the detection limit, but at a concentration less than three times the detection limit.

D. Anion and Cation Emissions

MOUDI stages with size ranges of 0.54 Fm to 0.31 Fm, 0.31 Fm to 0.17 Fm, and 0.17 Fm to 0.09 Fm for Idle were analyzed by IC for anion and cation emissions. At Notch 8, the same three stages, plus the 0.09 Fm to 0.056 Fm range were examined. Particulate mass loadings for the other stages were too small to permit analysis. The anions included chloride, nitrate, and sulfate ions; and the cations included ammonium and potassium ions. Analyses for bromine were also conducted, but no bromine was found in any of the samples. Table 6 presents the results for the anions and cations by particle size distribution.

TABLE 6. EXHAUST ANION AND CATION MASS EMISSIONS

Engine Condition	Fuel	Particle Size Range, Fm	Chloride Ion, mg/hr	Nitrate Ion, mg/hr	Dry Sulfate Ion, mg/hr	Ammonium Ion, mg/hr	Potassium Ion, mg/hr
Idle	0.3% Sulfur	0.54 - 0.31	1.8	6.8	70	91	34
		0.31 - 0.17	ND[1]	3.9	110	130	ND
		0.17 - 0.09	ND	9.8	120	170	120
	CARB diesel	0.54 - 0.31	15	3.6	36	120	ND
		0.31 - 0.17	6.6	2.9	26	33	96
		0.17 - 0.09	ND	12	17	ND	160
Notch 8	0.3% Sulfur	0.54 - 0.31	43	110	4,600	2,700	1,500
		0.31 - 0.17	17	93	5,100	3,800	2,700
		0.17 - 0.09	130	46	31,000	9,500	1,700
		0.09 - 0.056	ND	140	33,000	11,000	2,300
	CARB Diesel	0.54 - 0.31	230	170	1,500	580	69
		0.31 - 0.17	29	55	1,200	570	1,800
		0.17 - 0.09	90	100	2,900	2,500	ND
		0.09 - 0.056	230	88	3,500	3,500	ND

Notes: 1 - ND-none detected; below detection limit.

1. Chloride Ion Mass Emission Rates

Figures 10 and 11 show the chloride ion mass emission rates by particle size distribution for the two engine conditions. The chloride ion mass emission rates using CARB fuel were higher than for the 0.3 percent sulfur nonroad diesel fuel at both Idle and Notch 8.

Chloride ion mass emission rates at Notch 8 were the lowest for the 0.31 Fm to 0.17 Fm particle size range. At the 0.09 Fm to 0.056 Fm range with the 0.3 percent sulfur fuel, no chloride ion was detected. The chloride ion mass emissions were also greater for all size ranges with the CARB fuel, except for the 0.17 Fm to 0.09 Fm range at Notch 8.

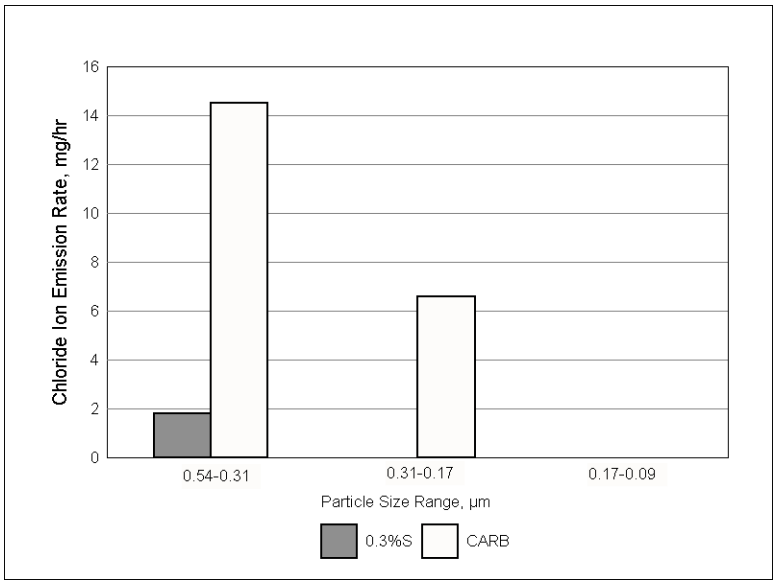

FIGURE 10. CHLORIDE ION MASS EMISSION RATE AT IDLE

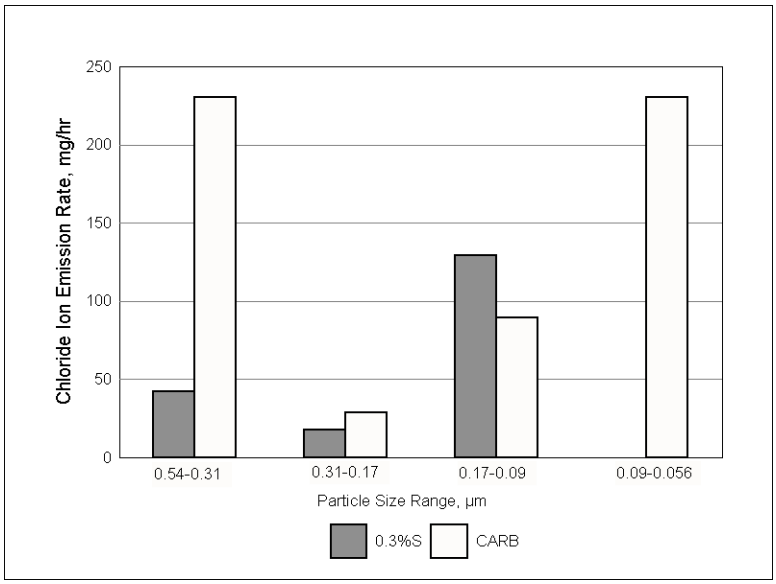

FIGURE 11. CHLORIDE ION MASS EMISSION RATE AT NOTCH 8

2. Nitrate Ion Mass Emission Rates

Figures 12 and 13 show the various nitrate ion mass emission rates by particle size distribution for the two engine conditions. Nitrate ion mass emission rates at Notch 8 were at least one order of magnitude greater than at Idle for both fuels. The differences in nitrate ion mass emission rates between the two fuels for all size ranges did not appear to be related to the nitrogen content in the fuel.

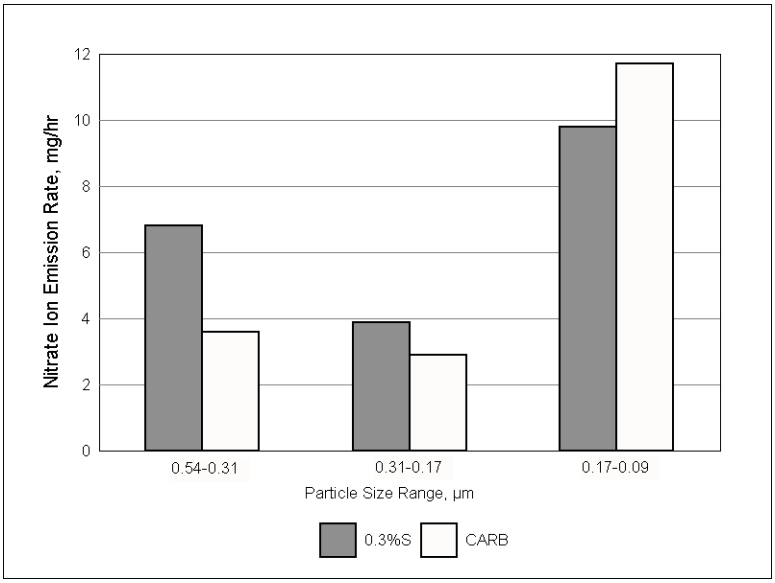

FIGURE 12. NITRATE ION MASS EMISSION RATE AT IDLE

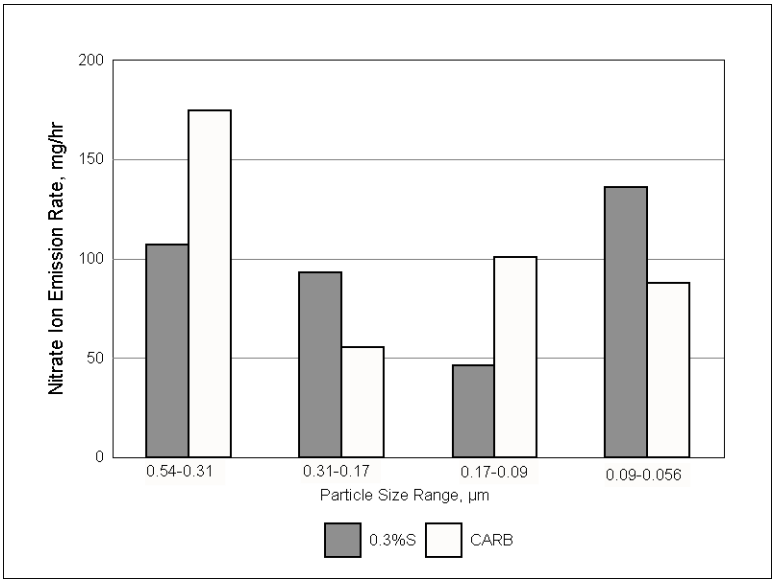

FIGURE 13. NITRATE ION MASS EMISSION RATE AT NOTCH 8

3. Sulfate Ion Mass Emission Rates

To isolate the specific effect of fuel sulfur content on change in particulate emissions, sulfate analyses were performed. Sulfate emissions are summarized in Table 7. Sulfate is reported here as "wet" sulfate, because sulfate is generally composed of sulfuric acid, H_2SO_4, with associated bound water. The hydration state of the sulfuric acid is very sensitive to the relative humidity in the PM filter weighing chamber. At 50 percent relative humidity in the weighing chamber, the hydration of one gram of sulfuric acid results in 1.3 grams of water per gram of H_2SO_4. This hydration means that the fraction of the total particulate mass due to the sulfate is 2.3 times the mass of the "dry" sulfate alone, because of the associated water.

Results given in Table 7 show that at Idle, sulfates contribute only a small percentage of the total PM, independent of the fuel. At Notch 8, however, sulfate made up over half of the total PM at the size range 0.09 to 0.056 Fm while using the 0.3 percent sulfur nonroad diesel fuel. For CARB diesel, which had a sulfur content of 50 ppm, sulfates contributed only 14 percent of the total PM at the same size range.

TABLE 7. SULFATE MASS EMISSION SUMMARY

Engine Condition	Fuel	Particle Size Range, Fm	Total[a] PM, mg/hr	"Dry" Sulfate, mg/hr	"Wet" Sulfate[b], mg/hr	"Wet" Sulfate, % of total PM
Idle	0.3% Sulfur	0.54 - 0.31	12,000	70	160	1
		0.31 - 0.17	14,000	110	260	2
		0.17 - 0.09	10,000	120	280	3
	CARB diesel	0.54 - 0.31	13,000	36	82	0.6
		0.31 - 0.17	12,000	26	59	0.5
		0.17 - 0.09	3,600	17	38	1
Notch 8	0.3% Sulfur	0.54 - 0.31	140,000	4,60	11,000	7
		0.31 - 0.17	86,000	5,100	12,000	14
		0.17 - 0.09	160,000	31,000	71,000	45
		0.09 - 0.056	140,000	33,000	75,000	53
	CARB Diesel	0.54 - 0.31	100,000	1,500	3,400	3
		0.31 - 0.17	66,000	1,200	2,600	4
		0.17 - 0.09	54,000	2,900	6,800	13
		0.09 - 0.056	58,000	3,500	8,000	14

Notes: a - Total PM for each MOUDI stage using Nucleopore filter media.
b - "wet" sulfate equals 2.3× "dry" sulfate.

Figures 14 and 15 show the sulfate mass emission rates by particle size distribution for the two engine conditions. The sulfate ion mass emission rates at Idle increased with decreasing particle size for the 0.3 percent sulfur fuel, and decreased with decreasing particle size with the CARB diesel.

Sulfate ion mass emission rates at Notch 8 increased with decreasing particle size for both fuels. The mass emission rates for sulfate ion with the 0.3 percent sulfur fuel were almost a factor of five times greater than with the CARB diesel.

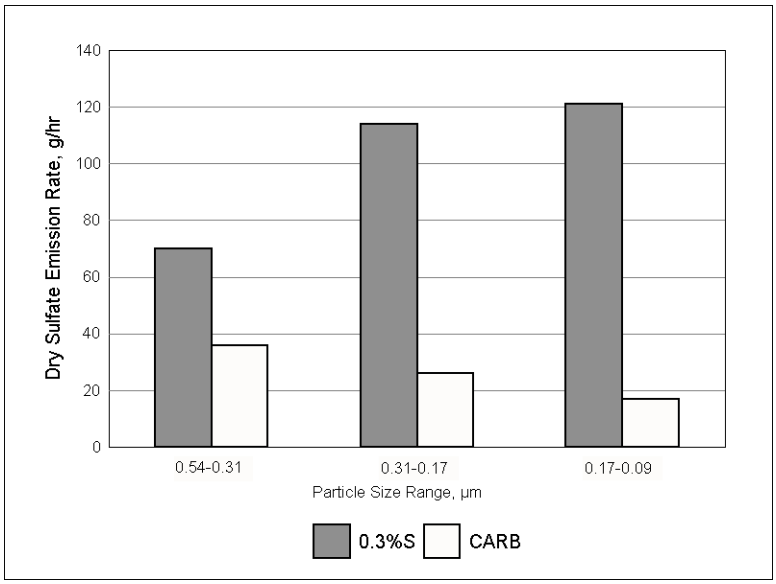

FIGURE 14. DRY SULFATE ION MASS EMISSION RATE AT IDLE

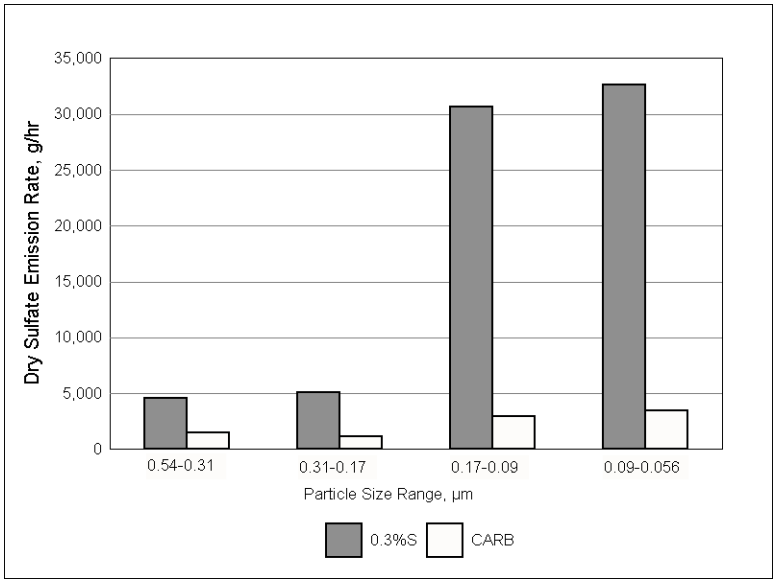

FIGURE 15. DRY SULFATE ION MASS EMISSION RATE AT NOTCH 8

4. Ammonium Emissions

Figures 16 and 17 show ammonium ion mass emission rates by particle size distribution for the two engine conditions. Ammonium mass emission rates at Idle increased with smaller particle size for the 0.3 percent sulfur fuel, and decreased with smaller particle size range with the CARB diesel. Overall, ammonium mass emissions were greater for the 0.3 percent sulfur fuel, except for the 0.54 to 0.31 Fm size range for CARB diesel. Ammonium ion mass emissions at Notch 8 increased with decreasing particle size for both fuels.

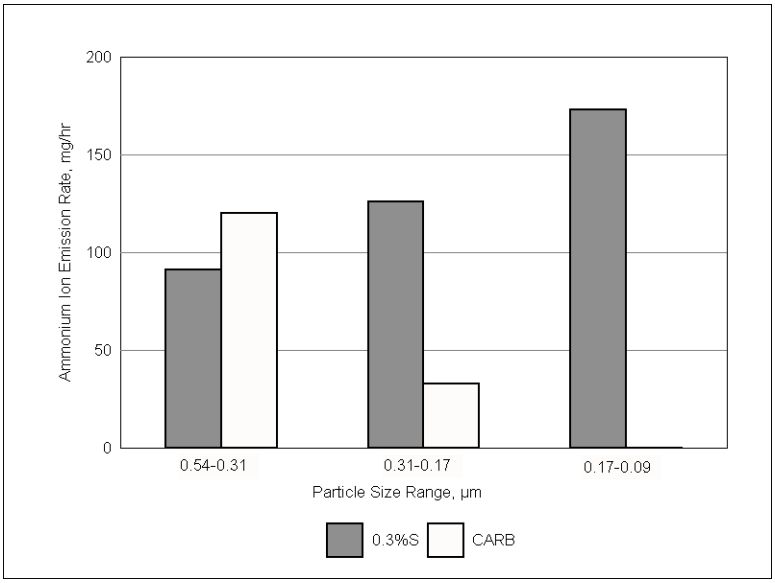

FIGURE 16. AMMONIUM ION MASS EMISSION RATE AT IDLE

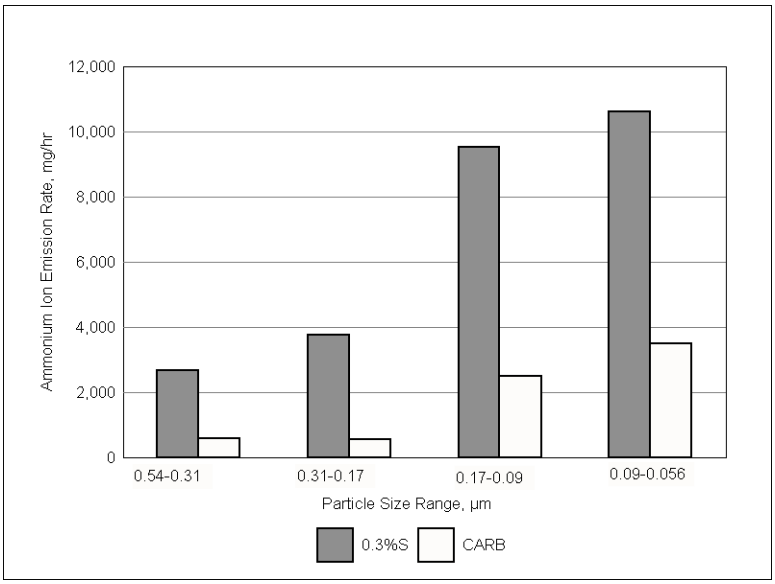

FIGURE 17. AMMONIUM ION MASS EMISSION RATE AT NOTCH 8

5. Potassium Ion Mass Emission Rates

Figures 18 and 19 show potassium ion mass emission rates by particle size distribution for the two engine conditions. No trends were noted in the potassium ion mass emission rates for any particle size range with either fuel or engine operating condition.

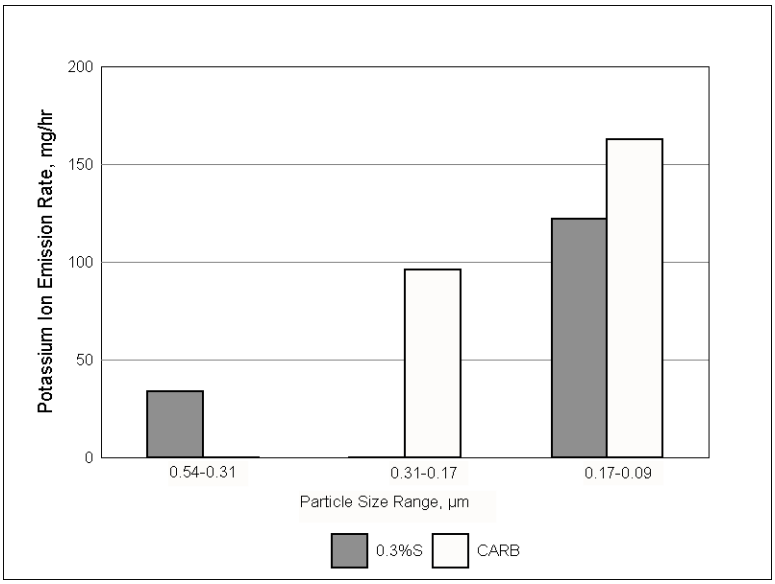

FIGURE 18. POTASSIUM ION MASS EMISSION RATE AT IDLE

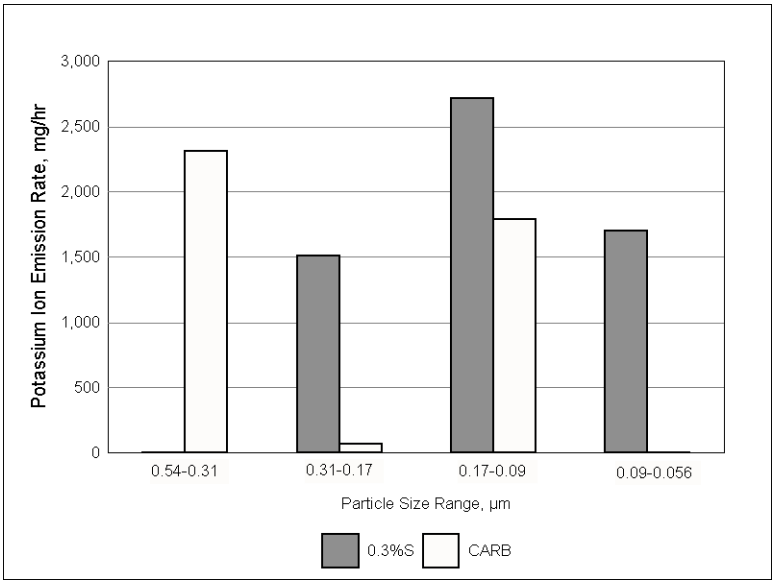

FIGURE 19. POTASSIUM ION MASS EMISSION RATE AT NOTCH 8

V. SUMMARY

Testing was performed to provide the ARB with data on the characterization of total particulate for various particle size fractions from a 4,400 hp GE locomotive. Two fuels were used in this study, a 0.3 percent sulfur nonroad diesel, and a CARB diesel. Sampling for particle sizing was conducted at two different operating conditions, Idle and Notch 8. Particulate characterization by particle size included volatile organic content, elemental analysis, and anion and cation levels.

Less than one percent of the particles were larger than 2.5 Fm for both fuels. The particle size distribution at Idle was monomodal, and at Notch 8 it was bimodal.

Total particulate mass emission was higher with the higher sulfur fuel for both operating conditions. Particulate emissions by particle size were similar for both fuels, down to a particle size range between 0.31 Fm to 0.17 Fm. At the smaller size ranges (0.17 Fm to 0.09 Fm, 0.09 Fm to 0.056 Fm, and less than 0.056 Fm), the CARB fuel produced lower masses of particles. This difference was also reflected in the fuel-derived VOF and the sulfate contribution to the total particulate mass. The sulfate mass emission rate was proportional to the fuel sulfur level.

Only five of 44 chemical elements were noted above the detection limit for the particle size ranges analyzed. The metal elements were mostly attributed to engine wear metals, and sulfur was associated with the fuel and lubricating oil. Except for sulfur, the metal elements were only a small fraction of the total particulate. At Idle and Notch 8, most of the detected elements were found in the larger particle size ranges (0.54 Fm to 0.31 Fm, 0.31 Fm to 0.17 Fm and 0.17 Fm to 0.09 Fm).

When operating at Idle, the 0.3 percent sulfur fuel showed a decrease in the VOF with decreasing particle size, while the CARB diesel yielded the highest VOF mass rate in the intermediate 0.31 Fm to 0.17 Fm size range. The percent of VOF attributed to unburned lubricating oil decreased with smaller particle sizes for both fuels at Idle, with the largest contribution occurring in the 0.54 Fm to 0.31 Fm size range. No consistent trends were noted for the Notch 8 condition.

For Notch 8, the average total particulate mass rate and the VOF were larger with the 0.3 percent sulfur fuel than with CARB diesel. Unburned lubricating oil derived VOF contributed about 57 percent of the VOF for the 0.3 percent sulfur fuel and about 64 percent for CARB diesel. At Notch 8, the unburned lubricating oil derived VOF was similar for both fuels, with the highest levels found in particles less than 0.056 Fm. The higher VOF levels with the 0.3 percent sulfur fuel were mostly fuel-derived VOF.

For the cations and anions, sulfate was highest with the higher sulfur fuel. Chloride, nitrate, and potassium ions were found to be only a small fraction of the total particulate. The mass emission rates for each ion were higher at Notch 8 than at Idle.

APPENDIX A

ELEMENTAL ANALYSIS RESULTS

Element Name	Element Symbol	Detection Limit (µg/filter)	Filter No.=	9226.6-895	9227.6-896	9228.6-897	9244.6-913	9245.6-914	9246.6-915	9247.6-916	9266.1-845	9352.6-931	9353.6-932	9354.6-933	9370.6-976	9371.6-977	9372.6-978	9373.6-979	9266.1-845	Blank	Blank
			Fuel =	HS	HS	HS	HS	HS	HS	HS	HS	CARB	CARB	CARB	CARB	CARB	CARB	CARB	CARB	47mm	37mm
			Test Run # =	R2	R2	R2	R6	R6	R6	R6	R6	R10	R10	R10	R14	R14	R14	R14	R14	Nucleopore	Pallflex
			PM Size Range, µm	0.54 - 0.31	0.31 - 0.17	0.17 - 0.09	0.54 - 0.31	0.31 - 0.17	0.17 - 0.09	0.09 - 0.06	<0.06 Pallflex	0.54 - 0.31	0.31 - 0.17	0.31 - 0.17	0.54 - 0.31	0.31 - 0.17	0.17 - 0.09	0.09 - 0.06	<0.06 Pallflex		
			Test Condition	Idle	Idle	Idle	Notch 8	Notch 8	Notch 8	Notch 8	Notch 8	Idle	Idle	Idle	Notch 8	Notch 8	Notch 8	Notch 8	Notch 8		
			Sample Results, µg/filter																		
Aluminum	Al	30		36.6	nd	nd	nd	nd	nd	nd	726	nd	nd	70.6	nd	33.5	nd	nd	625	0	649
Antimony	Sb	0.1		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Arsenic	As	0.1		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Barium	Ba	5		10.2	11.6	nd	nd	nd	nd	nd	326	nd	nd	17	nd	nd	nd	nd	275	0	264
Beryllium	Be	0.05		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Bismuth	Bi	0.1		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Boron	B	75		nd	nd	nd	nd	nd	nd	nd	919	nd	nd	nd	nd	nd	nd	nd	790	0	892
Cadmium	Cd	0.05		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Calcium	Ca	125		nd	134	nd	130	128	126	129	651	nd	nd	nd	nd	130	131	nd	571	129	632
Chromium	Cr	0.1		0.762	0.423	0.451	0.408	0.476	0.384	0.351	0.147	0.349	0.402	0.340	0.428	0.410	0.378	0.358	nd	0.52	0
Cobalt	Co	0.1		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Copper	Cu	0.1		nd	0.107	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Gallium	Ga	0.05		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Gold	Au	0.05		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Indium	In	0.05		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Iron	Fe	1		2.34	nd	1.1	nd	nd	nd	nd	1.44	nd	nd	nd	nd	nd	nd	nd	1.25	1.04	1.16
Lanthanum	La	0.1		0.152	0.114	0.385	0.339	0.134	nd	nd	0.207	0.145	nd	nd	nd	nd	0.146	nd	nd	0.126	0.204
Lead	Pb	0.05		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Lithium	Li	0.1		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Magnesium	Mg	0.5		nd	nd	nd	nd	nd	nd	1.65	0.702	nd	nd	nd	nd	nd	nd	nd	1.02	0	1.09
Manganese	Mn	1		2.17	nd	nd	1.92	1.03	nd	nd	nd	nd	1.79	nd	1.24	1.01	2.16	nd	nd	0	0
Mercury	Hg	0.1		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Molybdenum	Mo	0.1		nd	nd	nd	nd	0.153	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Nickle	Ni	0.1		0.265	nd	0.173	0.266	0.135	nd	nd	nd	nd	nd	0.239	nd	nd	nd	nd	nd	0	0
Palladium	Pd	0.05		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Phosphorus	P	0.25		nd	0.275	nd	nd	0.266	nd	nd	0.255	nd	nd	nd	nd	nd	nd	nd	0.416	0	0.266
Potassium	K	30		nd	nd	53.1	nd	47	nd	nd	1870	nd	nd	nd	nd	90.8	nd	75.9	1650	0	1630
Rubidium	Ru	0.05		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Selenium	Se	0.15		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Silicon	Si	50		85.3	85.6	55.5	60.5	77.1	55	nd	8840	nd	nd	129	nd	60.7	nd	nd	7920	0	8170
Silver	Ag	0.1		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Sodium	Na	2		2.78	nd	2.12	nd	2.77	nd	2.16	57.9	nd	3.41	nd	nd	nd	nd	nd	94.3	0	108
Strontium	Sr	2.5		nd	nd	nd	nd	nd	nd	nd	13.8	nd	nd	nd	nd	nd	nd	nd	12.1	4.46	11.4
Sulfur	S	1		3.11	2.84	3.95	1.63	3.65	9.07	9.65	5.19	2.2	2.38	1.08	1.57	1.78	2.56	2.38	2.32	0	2.27
Thallium	Tl	0.1		0.23	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Thorium	Th	0.1		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Tin	Sn	0.1		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Titanium	Ti	0.5		nd	nd	0.505	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Tungsten	W	0.15		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Uranium	U	0.05		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Vanadium	V	0.05		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Yttirum	Y	0.1		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Zinc	Zn	2.5		3.74	6.96	nd	3.21	nd	nd	nd	378	nd	nd	3.45	nd	nd	nd	nd	367	0	421
Zireonium	Zr	0.1		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Bromide	Br-	5		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0
Chloride	Cl	5		nd	nd	nd	13.5	5.2	nd	nd	nd	nd	8	8.9	nd	nd	nd	nd	nd	0	0

Element Name	Element Symbol	Filter No.=	9226.6-895	9227.6-896	9228.6-897	9244.6-913	9245.6-914	9246.6-915	9247.6-916	9266.1-845	9352.6-931	9353.6-932	9354.6-933	9370.6-976	9371.6-977	9372.6-978	9373.6-979	9266.1-845
		Fuel =	HS	HS	HS	HS	HS	HS	HS	HS	CARB	CARB	CARB	CARB	CARB	CARB	CARB	CARB
		Test Run # =	R2	R2	R2	R6	R6	R6	R6	R6	R10	R10	R10	R14	R14	R14	R14	R14
		PM Size Range, µm	0.54 - 0.31	0.31 - 0.17	0.17 - 0.09	0.54 - 0.31	0.31 - 0.17	0.17 - 0.09	0.09 - 0.06	<0.06 Pallflex	0.54 - 0.31	0.31 - 0.17	0.31 - 0.17	0.54 - 0.31	0.31 - 0.17	0.17 - 0.09	0.09 - 0.06	<0.06 Pallflex
		Test Condition	Idle	Idle	Idle	Notch 8	Notch 8	Notch 8	Notch 8	Notch 8	Idle	Idle	Idle	Notch 8	Notch 8	Notch 8	Notch 8	Notch 8
Aluminum	Al	Mass Emission Rate, µg/hr	T							T	T	T	T	T	T	T	T	
Antimony	Sb																	
Arsenic	As																	
Barium	Ba		T	T						T			655					T
Beryllium	Be																	
Bismuth	Bi																	
Boron	B																	
Cadmium	Cd																	
Calcium	Ca																	
Chromium	Cr		T							T								
Cobalt	Co																	
Copper	Cu			T														
Gallium	Ga																	
Gold	Au																	
Indium	In																	
Iron	Fe		T															
Lanthanum	La				T	T												
Lead	Pb																	
Lithium	Li																	
Magnesium	Mg								1515									
Manganese	Mn		T			T	T					T		T	T	T		
Mercury	Hg																	
Molybdenum	Mo						T											
Nickle	Ni		T		T	T	T						T					
Palladium	Pd																	
Phosphorus	P			T			T											
Potassium	K				T		T			T					69842		T	
Rubidium	Ru																	
Selenium	Se																	
Silicon	Si		T	T	T	T	T	T		T			T		T			
Silver	Ag																	
Sodium	Na		T		T		T		T			T						
Strontium	Sr																	
Sulfur	S		140	T	178	T	3352	8330	8862	T	T	T	T	T	T	T	T	
Thallium	Tl		T															
Thorium	Th																	
Tin	Sn																	
Titanium	Ti				T													
Tungsten	W																	
Uranium	U																	
Vanadium	V																	
Yttirum	Y																	
Zinc	Zn		T	T		T							T					
Zireonium	Zr																	
Bromide	Br-																	
Chloride	Cl					T	T					T	T					