SRI/USEPA-GHG-VR-33
August, 2005

Verification Report

EnviroFuels
Diesel Fuel Catalyzer
Fuel Additive

Prepared by:

Greenhouse Gas Technology Center
Southern Research Institute

Under a Cooperative Agreement With
U.S. Environmental Protection Agency

EPA REVIEW NOTICE

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Greenhouse Gas Technology Center

A U.S. EPA Sponsored Environmental Technology Verification (ETV) Organization

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This verification could not have happened without the extensive management, financial, and technical support provided by Genesee & Wyoming, Inc. and the St. Lawrence and Atlantic Railroad. Their most important contribution to the effort was the dedication of a locomotive to be tested. This required a one-week removal of the locomotive from revenue service for each of the baseline and treated fuel test periods. The tests also required maintenance mechanic time and coordination with the railroad's busy schedule. The GHG Center would especially like to thank Carl Belke of Genesee & Wyoming, George King II, Jeff Eichel, and Craig Rush of St. Lawrence and Atlantic Railroad for their generous help.

List of Acronyms and Abbreviations

A	amperes
bhp	brake horsepower
BSFC	brake-specific fuel consumption
CO	Carbon monoxide
CO_2	Carbon dioxide
DQO	data quality objective
DQI	data quality indicator
ETC	Environment Canada Environmental Technology Centre
ETV	Environmental Technology Verification
FTP	federal test procedure
g/bhp-h	grams per brake horsepower hour
g/h	grams per hour
g/min	grams per minute
gal/bhp-h	gallons per brake horsepower hour
GHG Center	Southern Research Institute Greenhouse Gas Technology Center
gph	gallons per hour
kW	kilowatt
mA	milliamperes
NO_X	nitrogen oxides
ppmv	parts per million by volume
QA/QC	quality assurance / quality control
QMP	Quality Management Plan
s_{n-1}	sample standard deviation
SLA	St. Lawrence and Atlantic Railroad
SO_2	sulfur dioxide
SO_4	sulfates
THC	total unburned hydrocarbons
TPM	total particulate matter
V	volts
Δ	delta (differential or change in a value)

1.0 INTRODUCTION

1.1. BACKGROUND

The U.S. Environmental Protection Agency's Office of Research and Development operates the Environmental Technology Verification (ETV) program to facilitate the deployment of innovative technologies. The program's goal is to further environmental protection by accelerating the acceptance and use of these technologies. Primary ETV activities are independent performance verification and information dissemination. Congress established ETV in response to the belief that many viable environmental technologies exist that are not being used for the lack of credible third-party performance data. With performance data developed under this program, technology buyers, financiers, and permitters will be better equipped to make informed decisions regarding new technology purchases and use.

The Greenhouse Gas Technology Center (GHG Center) is one of several ETV organizations. EPA's ETV partner, Southern Research Institute, manages the GHG Center. The GHG Center conducts independent verification of promising GHG mitigation and monitoring technologies. It develops Verification Test and Quality Assurance Plans (test plans), conducts field tests, collects and interprets field and other data, obtains independent peer-review input, reports findings, and publicizes verifications through numerous outreach efforts. The GHG Center conducts verifications according to the externally reviewed test plans and recognized quality assurance / quality control (QA/QC) protocols.

Volunteer stakeholder groups guide the GHG Center's ETV activities. These stakeholders advise on appropriate technologies for testing, help disseminate results, and review test plans and reports. National and international environmental policy, technology, and regulatory experts participate in the GHG Center's Executive Stakeholder Group. The group includes industry trade organizations, environmental technology finance groups, governmental organizations, and other interested parties. Industry-specific stakeholders provide testing strategy guidance within their expertise and peer-review key documents prepared by the GHG Center.

GHG Center stakeholders are particularly interested in transportation technologies with the potential to increase fuel economy and reduce GHG and criteria pollutant emissions. The Department of Energy reports that transportation carbon dioxide (CO_2) emissions were 32 percent of the total from all sectors during 2002 [1]. Railroad locomotives represent a significant fraction of the total. In 2002, railroads used approximately 7.5 percent of all diesel fuel in the transportation sector. In that year, railroad diesel fuel consumption was about 9.49×10^7 barrels crude oil equivalent, or 3.98×10^9 gallons [2]. Even incremental fuel efficiency or emission rate improvements would have a significant beneficial impact on nationwide air quality and railroad economics. Each 1 percent diesel fuel consumption reduction would reduce CO_2 emissions and fuel costs approximately 1 percent.

EnviroFuels, L.P. manufactures a diesel fuel additive and markets it to heavy-duty vehicle, off-road diesel engine, and railroad locomotive operators as the Diesel Fuel Catalyzer (catalyzer). The catalyzer's various embodiments are either patented or subject to patents pending. The catalyzer is a suitable verification candidate considering its potential environmental benefits and ETV stakeholder interest. Based on in-house testing on heavy-duty diesel vehicles, EnviroFuels claims that proper use of the catalyzer can reduce:

- fuel consumption (and corresponding CO_2 emissions) by 5 percent
- nitrogen oxide (NO_X) emissions by 12 to 18 percent
- unburned total hydrocarbon (THC) emissions up to 30 percent.

The GHG Center verified fuel consumption and pollutant emission changes attributable to the catalyzer during baseline and treated-fuel tests of an EMD GP-40-3 line-haul locomotive.

Baseline testing occurred during late August, 2004 at the St. Lawrence and Atlantic Railroad (SLA) switchyard in Auburn, ME while the locomotive was operating on a controlled lot of normal diesel fuel. Railroad maintenance personnel then treated the locomotive's fuel with the EnviroFuels catalyzer according to the manufacturer's instructions for a nine week break-in period. The test team returned and tested the locomotive's performance while operating on the treated fuel in late October, 2004.

The *Test and Quality Assurance Plan—EnviroFuels Diesel Fuel Catalyzer Fuel Additive* [3] (test plan) was the guiding document for the test campaign. It is available from the GHG Center Internet site at www.sri-rtp.com or the ETV Program site at www.epa.gov/etv. The test plan describes the verification's rationale, experimental design, testing procedures, data quality, and QA/QC goals. The vendor, peer-reviewers, testing contractors, the host facility, and the EPA Quality Assurance Team reviewed the test plan and the GHG Center revised it to address their comments prior to beginning the field work. The test plan meets the GHG Center's Quality Management Plan (QMP) requirements and also satisfies ETV QMP requirements.

The remainder of Section 1.0 describes the EnviroFuels catalyzer technology, the test locomotive, and provides an overview of the performance verification test campaign.

1.2. DIESEL FUEL CATALYZER

EnviroFuels literature states that the key to the catalyzer's performance is a compound that triggers chemical reactions which create inorganic polymer complexes of phosphorus and nitrogen on the surface of ferrous and non-ferrous metals. The formulators add the proprietary compound to refined mineral oil which, in turn, users administer to standard #2 diesel fuel.

The complexes, according to EnviroFuels statements, smooth and passivate the metal surface, improve reflectivity (or emissivity), and reduce oxygen reactivity. EnviroFuels states that the reduced oxygen reactivity reduces NO_X formation while the improved emissivity enhances combustion through reduced radiative losses from the flame front. This, combined with improved lubricity, reduces fuel consumption.

EnviroFuels' research indicates that at least six to eight weeks of regular service are required from the initial fuel treatment for the performance improvements to be fully realized in locomotive service. During this break-in period, EnviroFuels recommends a dosing rate of 640:1 in most locomotive applications. After that, the fuel must be treated at the normal 1280:1 ratio on an ongoing basis to maintain the effects.

1.3. TEST FACILITIES

The St. Lawrence and Atlantic Railroad, a division of Genesee and Wyoming, Inc., provided the test locomotive, resistive load bank, plant facilities, coordination with the test fuel supplier, and technical, mechanical, and managerial support.

The locomotive was built in 1980 and remanufactured to Title 40 CFR 92 Tier 0 standards in 2003. Its powerplant is an EMD 645 E3 two-cycle diesel engine rated at 3000 brake horsepower (bhp). Figure 1-1 shows the locomotive, the emissions test duct and equipment enclosure, the resistive load bank, the yard's main fuel tank, and other site features.

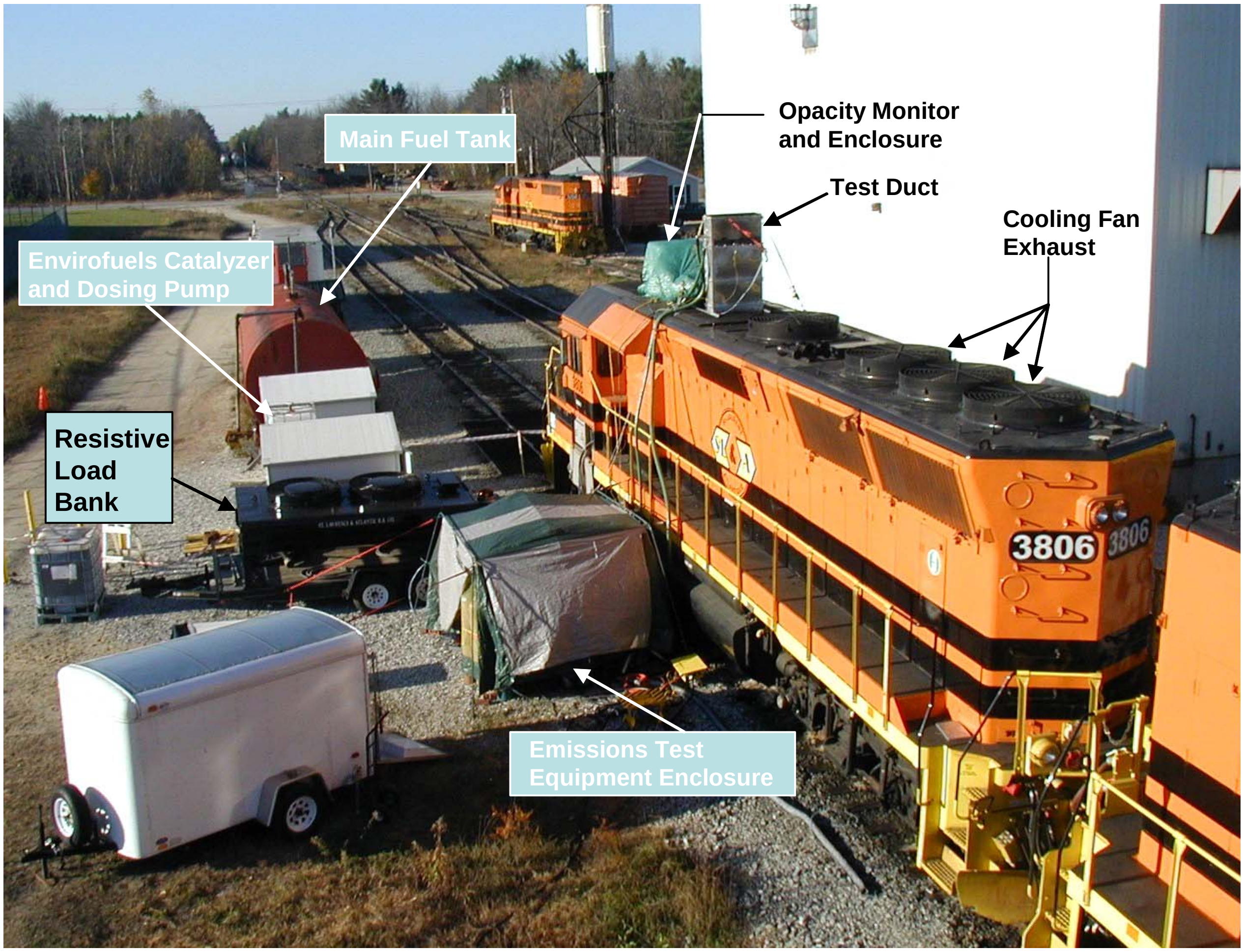


Figure 1-1. EMD Model GP-40-3 Locomotive and Test Equipment

The locomotive serves as the lead unit in a "mother - daughter" pair. The daughter is unpowered and its primary function is to spread the locomotive's tractive effort over more driving wheels. Some pertinent information is as follows:

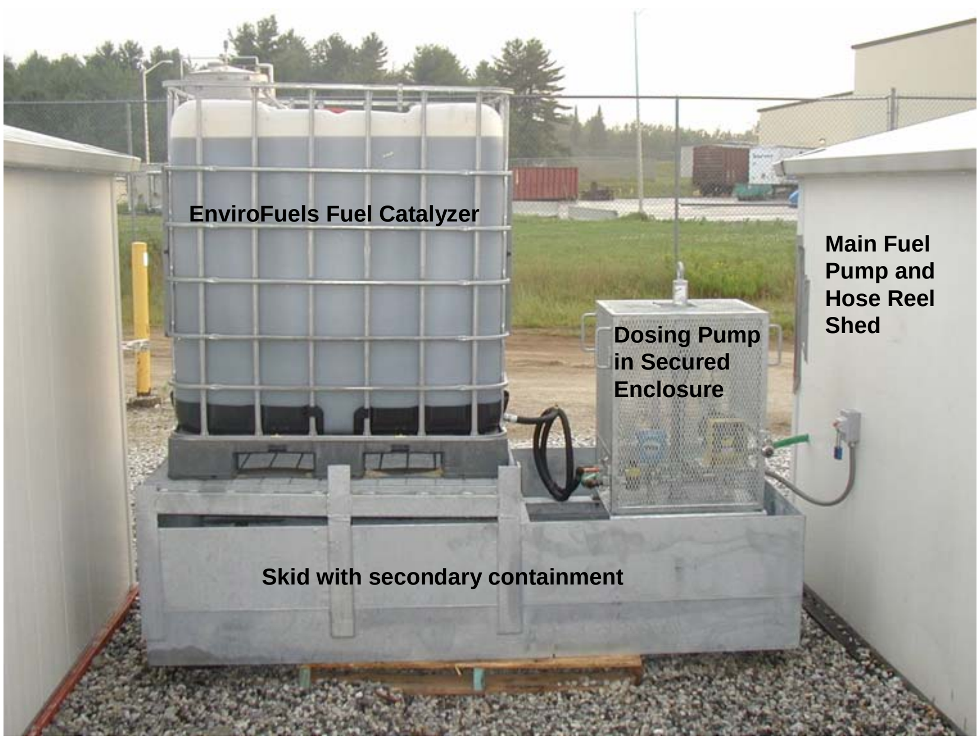
Locomotive	Horsepower	3000 bhp	Engine	Model	645E3
	Length, over couplers	59' 2"		Cylinders	16
	Width, over grab irons	10' 3 1/8"		Bore x stroke	9 1/16" x 10"
	Height, to top of cooling fan guards	15' 4 7/16"		Nominal idle speed	315 RPM
	Approximate dry weight	256,000 lb		Nominal full speed	900 RPM
				Operating Principle	2-cycle, turbocharged, unit injector
Main generator	Model	AR10		Family	3GETK0645MFA
Companion alternator	Model	D14	Air compressor	Cylinders	3
Auxiliary generator	Voltage	74 VDC	Air compressor	Capacity (900 RPM)	254 ft^3 / min
	Rating	10 kW			

SLA maintenance personnel connected the main generator directly to the resistive load bank which provided the electrical load. The test contractor, Environment Canada's Emissions Technology Centre (ETC) installed the test duct onto the locomotive's exhaust duct and located the opacity monitor adjacent to the test duct. Heated umbilicals conveyed the exhaust gas samples from the test duct probes to the emissions test equipment enclosure at ground level.

During all tests, SLA maintenance personnel connected the locomotive's air system to the shop air supply to prevent the air compressor from cycling unpredictably. All DC circuit breakers, except for the emergency shutdown and engine operating systems, were opened. This provided a constant, low-level load at the auxiliary generator. These provisions and the test team's direct measurements of the power supplied to the cooling fans (which were the only loads on the companion alternator) minimized the effects of changing parasitic loads on the test run results.

EnviroFuels provided the fuel catalyzer in a tote placed on a skid which incorporated its own secondary containment. A positive-displacement dosing pump was part of the skid. SLA personnel enabled it following the baseline tests. The yard's main fuel tank pump power supply controlled the dosing pump, which injected the catalyzer at the manufacturer's specified rate into the main fuel hose and nozzle assembly. This allowed a controlled amount of additive to be mixed in the fuel hose as SLA personnel refueled the locomotive over the break-in period and during the treated fuel tests. Figure 1-2 illustrates the catalyzer tote, skid, and dosing pump.

Figure 1-2. EnviroFuels Tote, Dosing Pump, and Skid



1.4. PERFORMANCE VERIFICATION OVERVIEW

The EnviroFuels Diesel Fuel Catalyzer performance verification parameters are brake horsepower-specific fuel economy, pollutant, and GHG emission changes associated with catalyzer use in the test locomotive. Section 2.0 of this report provides detailed test results on a "per notch" basis and as a weighted average using line-haul and switch service weightings. Reported parameters are:

- brake-specific fuel consumption rates, $BSFC_j$, for baseline and treated fuel, and the change, $\Delta BSFC_j$, for each notch j, gallons per brake horsepower hour (gal/bhp-h)
- line-haul and switch duty-cycle weighted brake-specific fuel consumption rates, $BSFC_{DC}$, and the change, $\Delta BSFC_{DC}$, gal/bhp-h
- brake-specific mass emission rates, E_{ij}, for baseline and treated fuel, and the change, ΔE_{ij}, for each pollutant or GHG species i at each notch j, grams per brake horsepower hour, g/bhp-h
- line-haul duty-cycle weighted brake-specific mass emission rates, E_{iDC}, and the change, ΔE_{iDC} for each emitted pollutant or GHG species i, g/bhp-h

Emissions measured during the tests were:

- CO_2, volume%
- Carbon monoxide (CO), parts per million by volume (ppmv)
- NO_X, ppmv
- total non-methane hydrocarbons, ppmv
- methane, ppmv
- total hydrocarbons (THC), ppmv
- total particulate matter (TPM), ppmv
- smoke opacity,%

The primary locomotive parameters of concern were:

- main generator (AR10) voltage
- main generator current
- engine fuel consumption, gallons per hour (gph)
- cooling fan power consumption, kilowatts (kW)

1.5. MEASUREMENT EQUIPMENT

Figure 1-3 is a summary schematic of the measurement equipment locations.

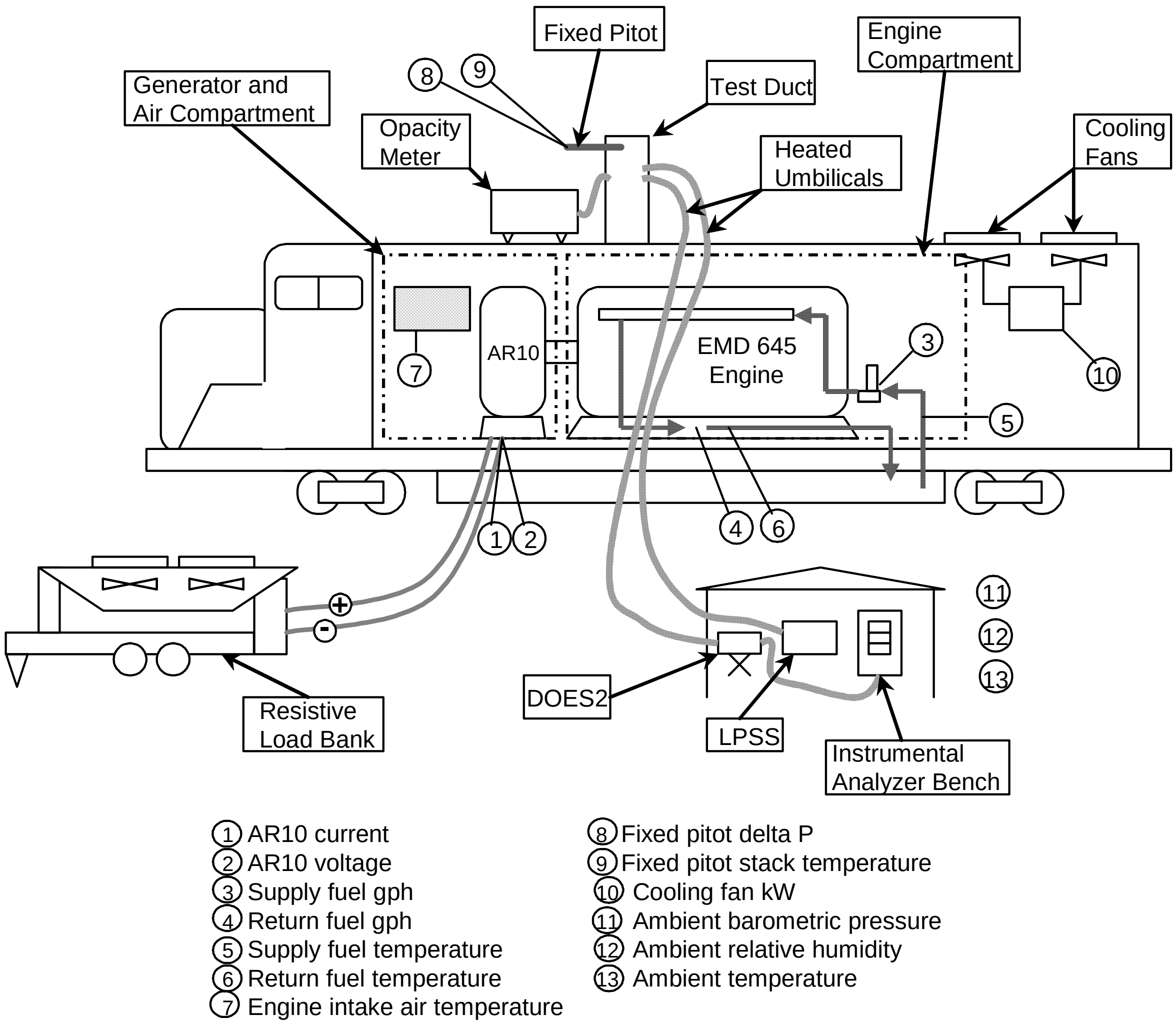


Figure 1-3. Measurement Equipment Locations

1.5.1. AR10 Main Generator Current and Voltage

The AR10 main generator electrical control cabinet contains the external resistive load bank connection bus bar. The field team leader installed the current and voltage sensors directly on the bus bar.

The Flex-Core CTL-502S/4KY106/CTA215N current sensor span was 0 - 4000 amperes (A). The July 9, 2004 calibration certificate showed that the 95% confidence interval for achieved accuracy was ± 0.046% of reading.

The Flex-Core VT8-014E voltage sensor span was 0 - 1000 volts (V). The July 9, 2004 calibration certificate showed that average calibration accuracy was ± 0.055% of reading.

Both sensors output a 4 - 20 milliamp (mA) signal to the ION 7600 datalogger whose March 18, 2004 calibration certificate indicates a ± 0.3% full scale port conversion accuracy. This is ± 0.06 mA, or ± 1.5% at a 4 mA input level.

1.5.2. Fuel Supply and Return Flow Meters and Fuel Temperature Sensors

The field team leader installed a Flow Technologies, Inc. FuelCom model FC05 flow meter into the engine's supply pipeline just downstream of the electric fuel circulation pump. He installed the return flowmeter downstream of the return fuel manifold, just upstream of the fuel tank return fitting. Figures 1-4 and 1-5 show the flow meter installations.

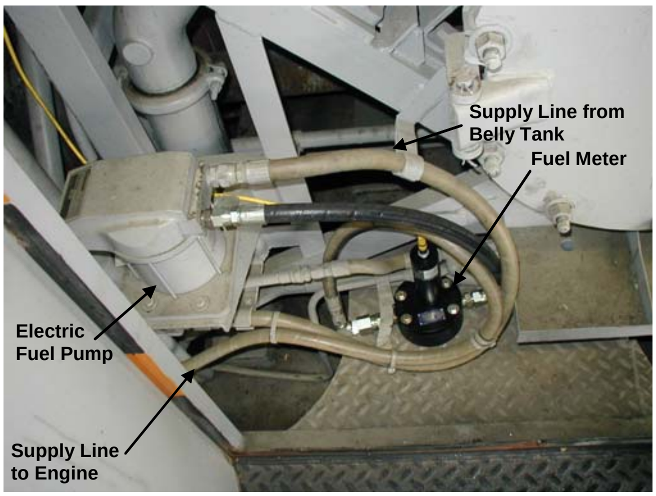


Figure 1-4. Supply Flowmeter

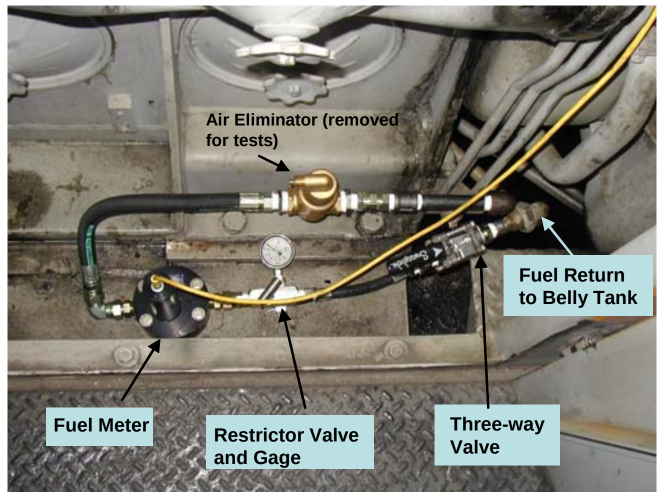


Figure 1-5. Return Flowmeter

The return flowmeter installation incorporated an air eliminator, restrictor valve, and pressure gauge as provisions to minimize air bubbles at the return flowmeter. The return fuel flow, as checked at the three-way valve, proved to be free of bubbles and the air eliminator later failed in service prior to the baseline tests, so it was removed.

External type K thermocouples, taped to the steel portion of the fuel pipelines and wrapped with insulation, served as fuel temperature sensors. The field team leader logged fuel temperatures at each notch with a Fluke model 52 thermocouple meter. Analysts used the average fuel temperature for engine horsepower fuel temperature compensation.

1.5.3. DOES2 and Instrumental Analyzers

Figure 1-6 shows the Dynamic Offroad Emissions Sampling System (DOES2) as installed in the field. The DOES2 is a partial-flow portable dilution sampling system for gaseous emissions. ETC developed the system as a modification of standard FTP methods (primarily 40 CFR 86 and 40 CFR 92) specifically designed for field testing of in-use vehicles. The DOES2 provides a dilute, conditioned sample to a portable instrumental analyzer bench. The analyzer bench is not in view in Figure 1-6. The test plan provides a DOES2 system schematic, a description, and discusses its relationship to 40 CFR 92 locomotive FTP test equipment specifications.

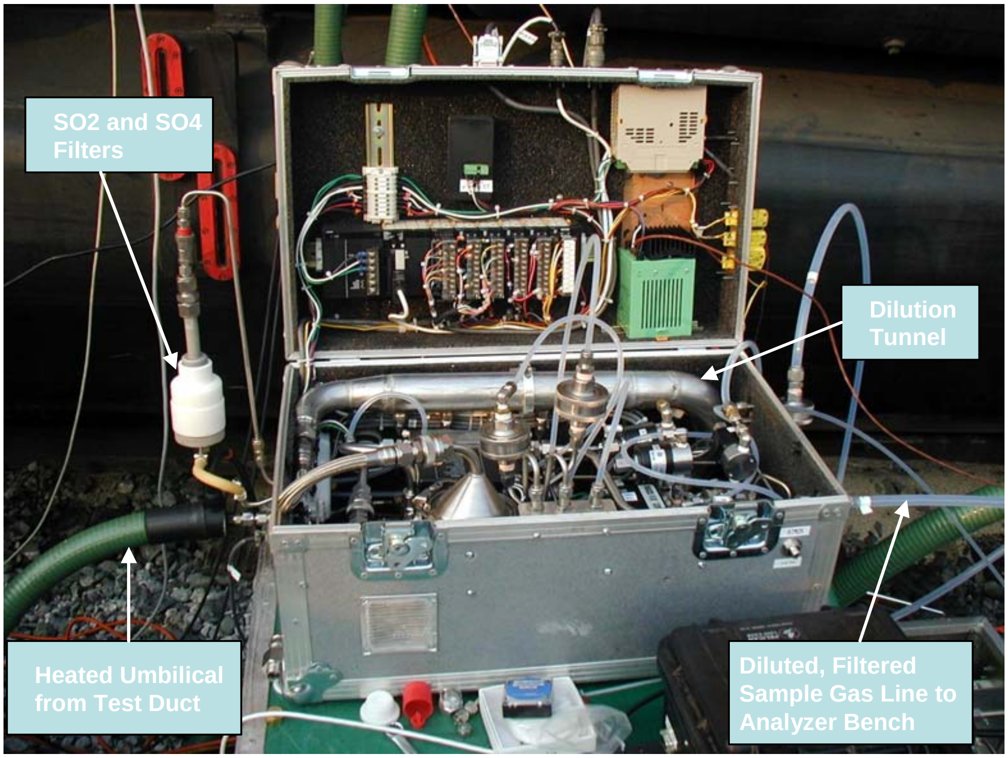


Figure 1-6. DOES2 Sampling and Dilution Apparatus

The analyzer bench contained the gaseous emissions analyzers, sample and calibration gas manifolds, and the necessary controls and sample pumps. California Analytical Instruments, Inc. manufactured the THC analyzer; others were by Horiba Instruments, Inc.

Figure 1-6 also shows the sulfur dioxide (SO_2) and sulfate (SO_4) teflon filter holder. The DOES2 moved a controlled volume of diluted stack gas through the filters for later laboratory analysis. Testers conducted SO_2 and SO_4 sampling for information only.

1.5.4. Locomotive Particulate Sampling System

Figure 1-7 shows the locomotive particulate sampling system (LPSS). Like the DOES2, it is a partial-flow dilution apparatus, but it passes a larger aliquot of dilute exhaust gas directly through the gravimetric TPM filters. ETC developed the LPSS as a modification of 40 CFR 92 test methods specifically for field TPM emissions determinations from larger vehicles. The test plan provides a system schematic, a description, and discusses the relationship between the LPSS and locomotive FTP test equipment specifications.

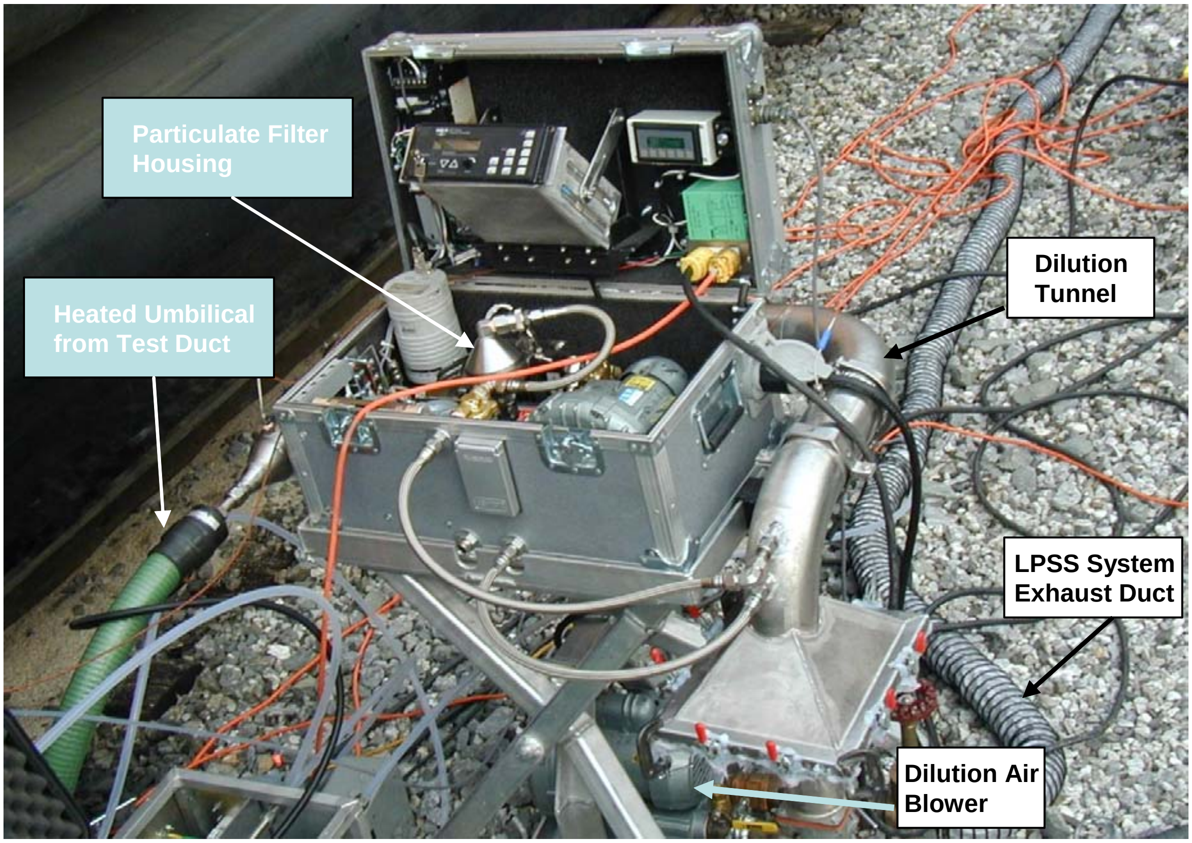


Figure 1-7. Locomotive Particulate Sampling System

1.5.5. Opacity Meter and Auxiliary Measurement Equipment

The Bosch - RT100A opacity meter extracted a partial exhaust sample from a probe installed in the test duct. The meter's sample pump conveyed the exhaust sample through a short length (about 3 feet) of teflon tubing through the opacity measurement cell. Testers shut the sampling pump off immediately following each 6-minute test period, which prevented fouling and reduced maintenance requirements.

Test personnel performed pre- and post-test stack gas volumetric flow rate traverses with a Type S pitot tube and thermocouple. They then installed the pitot at a fixed location and recorded stack temperature and velocity at that point throughout all test runs. Section 2.2.1 describes the stack gas volumetric flow rate determination as derived from this data set.

Testers installed a type K thermocouple in the engine's intake air plenum which was connected to a spare DOES2 temperature measurement channel. Analysts used the recorded air temperature during each test run and notch for engine horsepower air temperature compensation. ETC personnel also recorded ambient barometric pressure, relative humidity, and temperature as determined by a Visala model HM141 handheld instrument.

The field team leader recorded cooling fan real power consumption during each test run and notch as measured by an Extech model HVAC Trms Clamp Meter. The meter's accuracy for real power measurements was ± 5.0 percent.

2.0 VERIFICATION RESULTS

Although test personnel did measure fuel consumption directly as required by the locomotive FTP [4] and the test plan, significant calibration, accuracy, and operations problems with the fuel meters rendered the data invalid. This represented a significant departure from the FTP and test plan requirements. See Section 2.2.2 for a detailed discussion.

The test results, however, are valid for the baseline / treated fuel comparisons. The "carbon balance method," presented at §86.1382-94 in the diesel heavy-duty engine FTP [5], is the basis for all brake horsepower-specific results presented here. This method requires exhaust gas volumetric flow determinations with a constant volume sampling (CVS) system. The results reported here employed the 40 CFR 60 Appendix A Method 2 traverses and stationary pitot monitoring specified in the test plan's Table 3-3 instead of a CVS system. Section 3.1 of this report discusses the accuracy differences between the CVS system and the Method 2 techniques.

The results reported here represent the brake-specific fuel consumption (BSFC) and emission rate changes seen during the test locomotive's operations under field conditions at the host facility. These results may differ from those at other locomotives, test methods, or host facilities. BSFC and brake-specific gaseous emissions showed statistically significant improvements at the majority of the operating notches. Line-haul duty cycle-weighted BSFC and gaseous emissions (except for NO_X, which was not statistically significant) also improved. Switch duty cycle-weighted BSFC and all gaseous emissions showed statistically significant improvements. TPM emissions, however, increased during the treated fuel tests.

The following tables present the changes between the baseline and treated fuel BSFC as gallons per brake horsepower hour (gal/bhp-h) and for brake-specific emissions as grams per brake horsepower hour (g/bhp-h). Positive numbers indicate a BSFC improvement or emission rate increase. Negative numbers indicate an emission rate decrease. For example, notch 2 BSFC improved by 0.009 ± 0.003 gal/bhp-h, CO emissions decreased by 0.20 ± 0.07 g/bhp-h, and TPM increased by 0.09 ± 0.04 g/bhp-h.

Uncertainty values are the 95 percent confidence interval about the mean results for six baseline and six treated fuel test runs. Student's T test, evaluated at 95 percent certainty, provided the estimate of statistical significance.

Table 2-1. BSFC and Brake-Specific Emission Rate Change, Per Notch Values

Notch	1	2	3	4	5	6	7	8
BSFC, gal/bhp-h	*	0.009 ± 0.003	0.010 ± 0.004	0.009 ± 0.003	0.005 ± 0.003	0.010 ± 0.007	0.004 ± 0.003	*
CO, g/bhp-h	- 0.34 ± 0.17	- 0.20 ± 0.07	- 0.36 ± 0.08	- 1.00 ± 0.19	- 1.3 ± 0.6	- 1.2 ± 0.8	- 1.2 ± 0.7	- 0.51 ± 0.08
CO_2, g/bhp-h	*	- 80 ± 20	- 90 ± 30	- 70 ± 30	- 40 ± 30	- 90 ± 60	- 30 ± 30	*
NO_X, g/bhp-h	*	- 1.0 ± 0.9	- 1.5 ± 0.8	- 0.9 ± 0.5	*	*	*	*
THC, g/bhp-h	- 0.11 ± 0.04	- 0.09 ± 0.07	*	- 0.06 ± 0.03	- 0.03 ± 0.02	- 0.06 ± 0.02	- 0.05 ± 0.02	- 0.03 ± 0.02
TPM[a], g/bhp-h	*0.07 ±0.06*	*0.09 ±0.04*	*0.11 ±0.04*	*0.11 ±0.04*	*0.13 ±0.04*	*0.18 ±0.07*	*0.28 ±0.07*	*0.30 ±0.07*

* Not statistically significant
[a]TPM results represent increased emissions as compared to baseline tests.

Table 2-2. BSFC and Brake-Specific Emission Rate Change, Per Notch Percentage of Baseline								
Notch	1	2	3	4	5	6	7	8
BSFC	*	- 13 ± 4%	- 15 ± 6%	- 13 ± 4%	- 8 ± 5%	- 15 ± 11%	- 7 ± 5%	*
CO	- 33 ± 17%	- 31 ± 11%	- 36 ± 9%	- 50 ± 10%	- 40 ± 20%	- 30 ± 20%	- 50 ± 30%	- 50 ± 8%
CO_2	*	- 13 ± 4%	- 15 ± 6%	- 13 ± 5%	- 8 ± 5%	- 15 ± 11%	- 6 ± 5%	*
NO_X	*	- 9 ± 7%	- 14 ± 8%	- 8 ± 5%	*	*	*	*
THC	- 32 ± 12%	- 30 ± 30%	*	- 27 ± 12%	- 13 ± 10%	- 22 ± 9%	- 22 ± 10%	- 17 ± 12%
TPM[a]	*40* *±40%*	*60* *±30%*	*42* *±17%*	*42* *±16%*	*50* *±18%*	*70* *±30%*	*140* *±30%*	*170* *±40%*
* Not statistically significant [a]TPM results represent increased emissions as compared to baseline tests.								

Duty cycle-weighted emissions in Table 2-3 result from weighting factors applied to the emissions and bhp produced during each notch. Title 40 CFR 92.132 provides the line-haul and switch duty weighting factors and the test plan included them for reference.

Table 2-3. Duty Cycle-Weighted BSFC and Emission Rate Change						
Line-haul Duty Cycle						
Parameter	BSFC, gal/bhp-h	CO, g/bhp-h	CO_2, g/bhp-h	NO_X, g/bhp-h	THC, g/bhp-h	TPM[a], g/bhp-h
Delta	0.003 ± 0.002	- 0.75 ± 0.14	- 30 ± 20	*	- 0.06 ± 0.03	*0.23* *±0.08*
Percentage of baseline	5 ± 4%	- 44 ± 8%	- 5 ± 4%	*	- 22 ± 12%	*100* *±40%*
Switch Duty Cycle						
Delta	0.008 ± 0.003	- 0.9 ± 0.3	- 70 ± 30	- 1.2 ± 0.9	- 0.12 ± 0.8	*0.12* *±0.04*
Percentage of baseline	10 ± 4%	- 39 ± 12%	- 10 ± 4%	- 9 ± 7%	- 27 ± 18%	*46* *±18%*
* Not statistically significant [a]TPM results represent increased emissions as compared to baseline tests. TPM emissions remained below the Tier 0 standards (0.60 and 0.72 g/bhp-h for line-haul and switch duty cycles, respectively) for all baseline and treated fuel test runs.						

The test campaign did not quantify engine bhp at the low and high idle notches, so this report does not include those brake horsepower-specific results. Table 2-4 shows the changes in CO emissions for the idle notches. Other emissions changes were not statistically significant for the idle notches.

Table 2-4. CO Emission Rate Change at Idle		
	Low Idle	High Idle
Delta, g/bhp-h	- 100 ± 50	- 110 ± 40
Percentage of baseline	- 34 ± 16%	- 37 ± 14%

In general, smoke emissions improved over the baseline with statistically significant changes occurring for notches 3 through 7, depending on the averaging algorithm. For example, baseline opacities ranged between approximately 25 and 30 percent for notches 5 and 6 and treated fuel opacity ranged between approximately 10 and 17 percent for those notches. Section 2.3 presents the results as charts.

The GHG Center's field team leader and ETC personnel installed all measurement equipment prior to the test campaign. SLA also conducted the locomotive's normal 92-day Federal Railroad Administration safety inspection. SLA and EnviroFuels coordinated setup of the fuel catalyzer skid and acquisition of test support equipment (generator, manlift, etc.). SLA emptied the locomotive's belly tank and had it cleaned prior to filling it with fuel from a controlled lot. Irving Oil, the fuel supplier, controlled the fuel source by providing all the railroad's fuel from a single bulk tank located in Portland, ME throughout the baseline, break-in, and treated fuel test periods. Irving Oil certified that all fuel delivered to SLA's Auburn facility came from this controlled lot.

Testing began on August 16, 2004, with Title 40 CFR 60, Appendix A, Method 2 stack gas velocity traverses and cyclonic flow angle measurements while the locomotive was operating at each notch, under load. The test crew then completed six valid test runs on August 20, 2004.

At the completion of the baseline tests, SLA personnel administered the EnviroFuels fuel catalyzer to the fuel remaining in the locomotive's belly tank and enabled the dosing pump.

The break-in period, which incorporated all the locomotive's normal over-the-road operations, extended from August 21 through October 23, 2004. The locomotive consumed approximately 35,000 gallons of treated fuel during this period and required no maintenance or repair other than daily inspections. SLA personnel logged the dosing pump's counter at the end of each refueling and forwarded the results to the GHG Center. At EnviroFuels' recommendation, SLA changed the dosing ratio from approximately 640:1 to approximately 1280:1 on October 10. This allowed the locomotive to burn approximately 6700 gallons of fuel at the latter ratio prior to the treated fuel test runs.

Treated fuel test runs began on October 24, 2004, after ETC had set up their equipment on October 23. The tests series was the same as that for the baseline runs: a series of Method 2 traverses at each notch under load, followed by six valid test runs, finishing with a final series of Method 2 traverses on October 28, 2004.

A locomotive warmup cycle preceded each test run. The warmup cycle consisted of operating the locomotive under load for 3 minutes at each notch (6 minutes at notch 8), starting at low idle. The operator then returned to low idle over 1 minute. Each test run then commenced within 15 minutes. Test runs began at low idle, cycling through each of the notches in turn. The locomotive operated at each notch for 20 minutes (15 minutes at notch 8), with particulate sampling during the first 6 minutes. Testers obtained gaseous emissions, opacity, and cooling fan power consumption data during the 4th through 6th minute for the idle notches, the 6th minute for notches 1 through 7, and the 15th minute for notch 8. The locomotive's physical and electrical configuration prevented gathering data during the dynamic braking mode.

2.1. ENGINE BHP

Table 2-5 presents the compensated gross engine brake horsepower for the baseline and treated fuel tests.

Table 2-5. Compensated Brake Horsepower at Engine

Notch	1	2	3	4	5	6	7	8
Baseline mean bhp	288	502	866	1157	1555	2100	2675	2962
Sample standard deviation (s_{n-1})	4	4	5	6	11	200	17	14
Treated fuel mean bhp	293	540	920	1226	1645	2320	2870	2905
s_{n-1}	9	20	20	15	19	40	20	5

The locomotive produced more power during the treated fuel tests, except at notch 8. It was difficult to discern performance changes between notches 7 and 8 for the treated fuel tests, except that the engine seemed to run more smoothly at notch 8. The relationship between the AR10 generator power demand and the engine's governor caused speed variations (or "hunting") at notches 6 and 7 throughout all the tests. This was especially evident at notch 6 during the baseline tests, as shown by the sample standard deviation in Table 2-5.

The test plan equation for brake horsepower used 0.715 for the generator efficiency and 0.7457 kW per bhp. This is incorrect. The locomotive manufacturer states that 0.715 is the combined value for the AR10's efficiency and the kW to bhp conversion factor. The correct equation for engine bhp is:

$$bhp_j = \frac{kW_{AR10}}{0.715} \qquad \text{Eqn. 2-1}$$

Where:

bhp_j = mean mechanical power for mode j, bhp
kW_{AR10} = mean main generator power output, kW
(note that kW_{AR10} is $V_{AR10} \cdot A_{AR10} / 1000$)
0.715 = combined AR10 electrical efficiency and kW to horsepower conversion

The test plan also included constant default load values for the mechanical accessory horsepower, such as the main air blower, traction motor blower, unloaded air compressor, and unloaded auxiliary DC generator. These loads cannot be constant at each notch because the engine speed varied from about 254 to 914 revolutions per minute between low idle and notch 8. Use of a single default value for the unloaded air compressor, for example, is not realistic. These parasitic loads did not vary between the baseline and treated fuel tests, so the verification results were not affected by them. Analysts therefore did not allow for them in the results. The reader should note, however, that locomotive emissions test results often include mechanical accessory horsepower default values for regulatory purposes (see 40 CFR 92.2).

The results have been compensated with factors provided by the manufacturer, per industry practice, to 31.8 ^{o}API gravity, 68 ^{o}F engine intake air temperature, and 29.85 "Hg absolute atmospheric pressure.

Figure 2-1 shows the AR10 voltage and current traces for a typical individual test run.

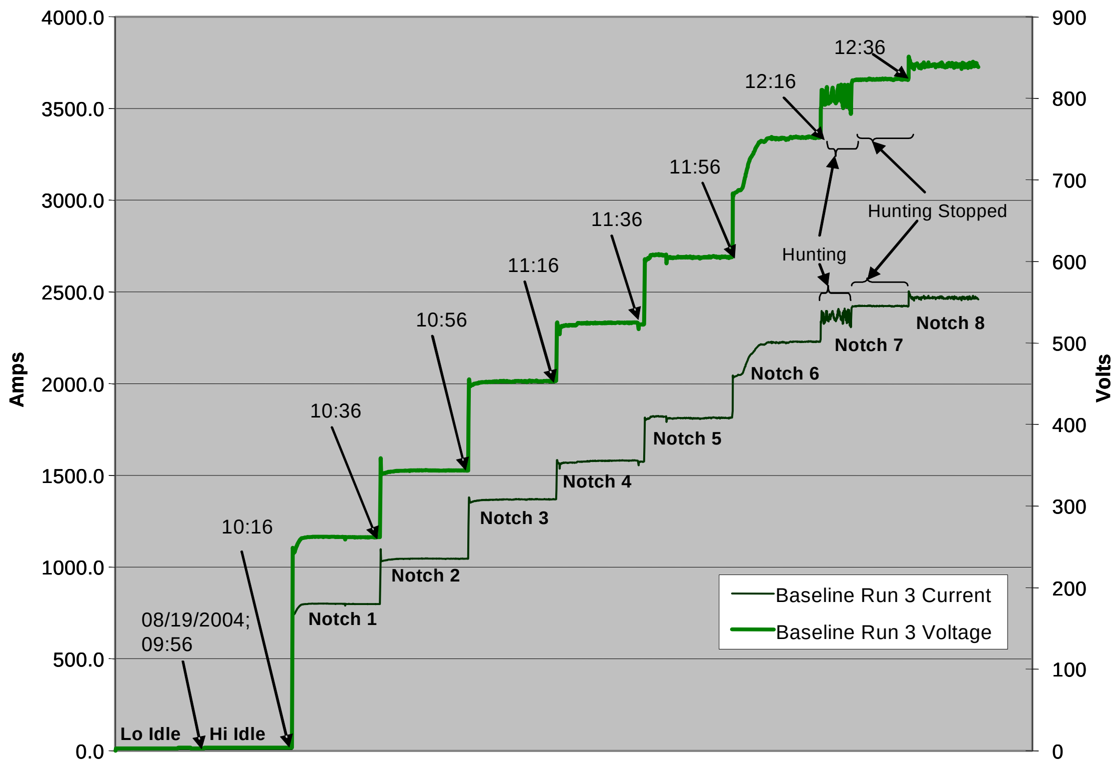


Figure 2-1. AR10 Generator Performance

It was sometimes possible to stop the engine's hunting during notches 6 and 7 by applying manual force to the governor control bar at certain points in the hunting cycle. Figure 2-1 shows this effect at notch 7. Note, however, that the performance results quoted here do not include time periods during which the engine's operation was manually forced.

Cooling fan power consumption ranged between approximately 10 and 120 horsepower (depending on the notch setting) for the baseline tests. The fans consumed between 0 and approximately 90 horsepower during the treated fuel tests.

For reference, Table 2-6 shows the mean exhaust gas temperatures as measured at point number 3c in the temporary test duct (see Figure 2-5) and mean engine intake air temperatures.

Table 2-6. Mean Exhaust Gas and Engine Intake Air Temperatures

Notch	Lo Idle	Hi Idle	1	2	3	4	5	6	7	8
Baseline exhaust, °F	223	201	297	388	489	581	669	732	718	720
s_{n-1}, °F	8	2	3	12	10	8	4	6	4	6
Engine intake air, °F	76	76	77	77	77	78	77	76	77	77
s_{n-1}, °F	6	5	5	9	2	2	2	2	3	4
Treated ehaust, °F	239	172	230	315	424	511	599	655	667	671
s_{n-1}, °F	32	7	26	35	32	28	29	96	92	91
Engine intake air, °F	49	49	49	50	52	52	55	58	60	60
s_{n-1}, °F	8	8	7	6	6	6	7	6	6	4

2.2. BRAKE-SPECIFIC FUEL CONSUMPTION

The FTP procedures for calculating fuel consumption correlate the exhaust gas carbon content with the actual exhaust gas volumetric flow in standard cubic feet per minute, the carbon available in the fuel, and the fuel's density, to yield the engine's fuel consumption rate in gph. This is known as the carbon balance method.

The DOES2 analyzers provided the THC, CO, and CO_2 carbon content (Section 2.3.1). The following subsection discusses acquisition of the volumetric flow rate data. The test fuel met all 40 CFR 92.113 specifications except that fuel density was 31.8 ^{o}API instead of 32 ^{o}API as specified by the CFR. ETC used 86.5 mass percent carbon and 13.8 mass percent hydrogen based on #2 diesel fuel analyses performed in 2003 for a New York City project. For reference, §86.1342-94 (d) (1) (ii) (C) cites the average carbon to hydrogen ratio as 1:00 : 1.80, or approximately 86.96 and 13.00 mass percent carbon and hydrogen, respectively. The GHG Center considers the fuel density and fuel carbon values to be identical between the baseline and treated fuel tests because the supplier lifted all fuel from the same storage tank during the test campaign.

The fuel consumption rate, divided by the compensated bhp (Section 2.1), yields the BSFC. The following tables provide the test results. This report cites the carbon balance method rather than the directly-measured fuel consumption results for the reasons noted in Section 2.2.2.

Note that the tables omit BSFC for the idle notches because the AR10 generator was producing negligible power and the engine's frictional and parasitic loads were not quantified. This means that a BSFC calculation would be meaningless for those individual notches.

Table 2-7. Mean Fuel Consumption and Engine RPM Per Notch Values

Notch	Lo Idle	Hi Idle	1	2	3	4	5	6	7	8
Baseline gph	4.4	5.3	21	34.5	60	77	99	144	154	154
s_{n-1}	0.8	0.4	1.6	0.9	3	3	2	8	6	6
Engine RPM	254	320	300	384	492	568	651	732	828	912
Treated Fuel gph	4.9	5.3	19.9	32.0	54.4	71	96	132	155	154
s_{n-1}	0.2	0.3	1.2	1.5	1.6	2	4	7	8	7
Engine RPM	254	319	317	388	498	573	655	733	830	914

Table 2-8. Mean BSFC Per Notch Values, gal/bhp-h

Notch	1	2	3	4	5	6	7	8
Baseline	0.075	0.0688	0.070	0.067	0.064	0.067	0.0577	0.0521
s_{n-1}	0.006	0.0019	0.004	0.002	0.002	0.007	0.0018	0.0018
Treated Fuel	0.068	0.060	0.0593	0.058	0.058	0.057	0.054	0.053
s_{n-1}	0.004	0.002	0.0017	0.002	0.003	0.004	0.003	0.002

Figures 2-2 and 2-3 illustrate the per-notch BSFC for each test run.

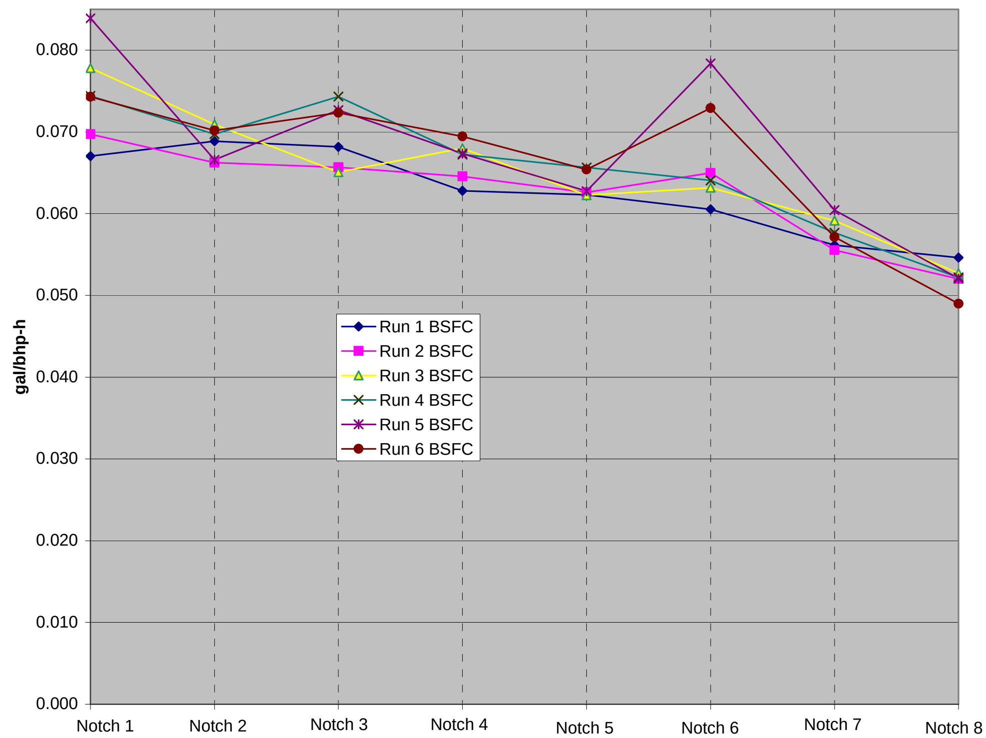


Figure 2-2. Baseline Run-Specific BSFC

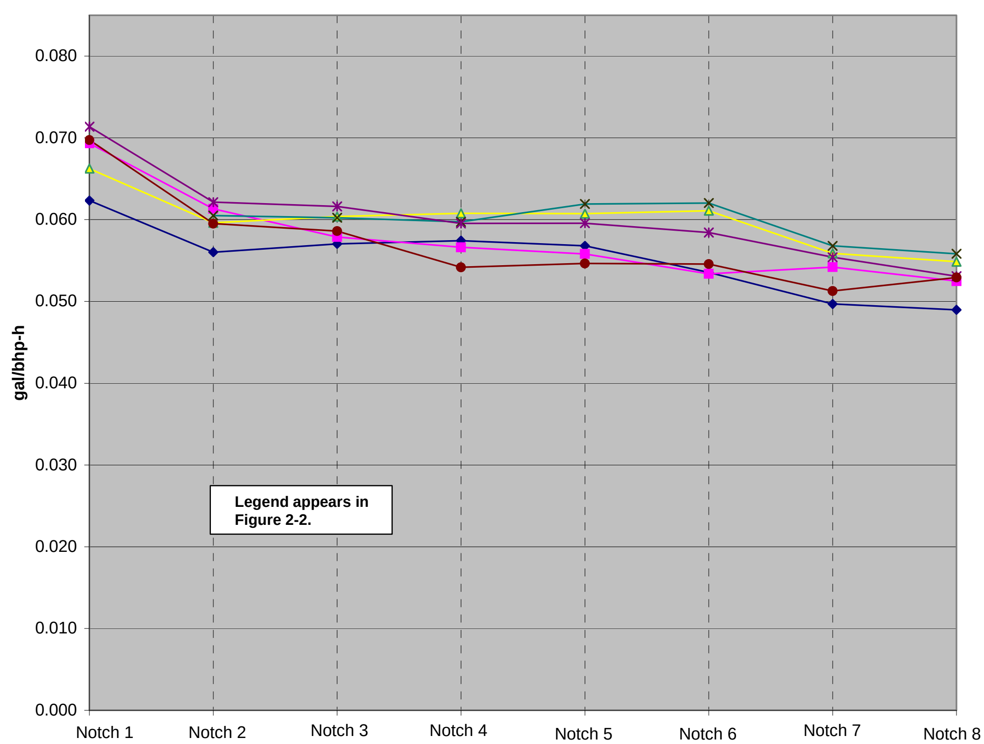


Figure 2-3. Treated Fuel Run-Specific BSFC

Table 2-9 provides the duty cycle-weighted BSFC.

Table 2-9. Mean Duty Cycle-weighted BSFC, gal/bhp-h		
	Line-Haul	**Switch**
Baseline	0.0600	0.076
s_{n-1}	0.0011	0.002
Treated Fuel	0.057	0.068
s_{n-1}	0.002	0.002

Table 2-9 incorporates data from 6 runs for the baseline fuel and 5 runs from the treated fuel. The treated fuel results omit data from Run 4. Instrumental analyzer problems occurred during notch 1 of this run so the duty cycle-weighted BSFC calculation is invalid.

Figure 2-4 shows the relationship between fuel consumption and total compensated bhp for both fuel conditions. The figure highlights possibly anomalous results for the baseline tests because it appears that mean bhp increased from notch 7 to notch 8 while fuel consumption remained approximately the same.

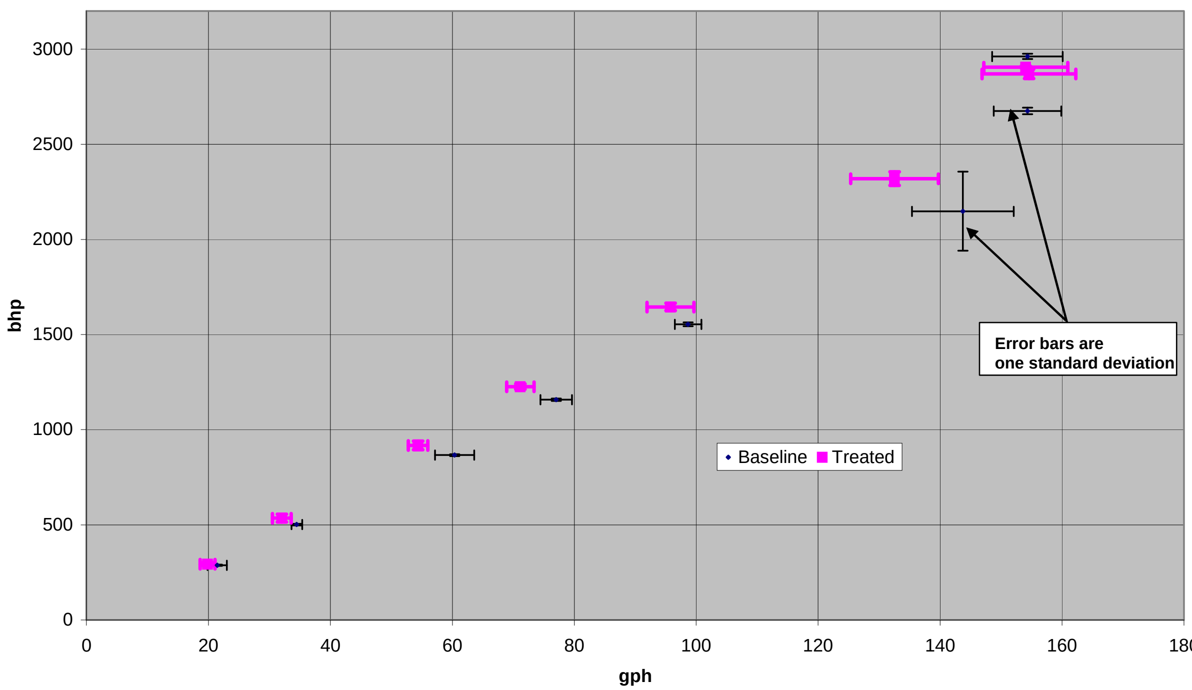


Figure 2-4. Fuel Consumption verses Brake Horsepower

The error bars, however, indicate that fuel consumption could also have either increased or decreased between notches 7 and 8. Isolated results like these should be interpreted with caution. For example, several thunderstorms moved through the area during some baseline test runs. Even though all test parameters remained within valid limits, this could have affected baseline variability. SLA personnel noted that the locomotive's control algorithms had been customized for the mother / daughter application, and this may have affected performance. Quantification of the effects of any of these influences is impossible without further testing.

2.2.1. Exhaust Gas Volumetric Flow Rate

Test personnel performed complete Method 2 traverses with a type S pitot and type K thermocouple at each notch:

- immediately before the first baseline test run
- immediately before the first treated fuel test run
- immediately following the last treated fuel test run

The standard locomotive warmup cycle (Section 2.0) preceded each traverse and the elapsed time for each notch was approximately the same as for a regular test run. Testers allowed the engine to equilibrate for at least 6 minutes at each notch to ensure stable operating conditions before starting the traverse. The traverses included differential pressure (ΔP) and temperature measurements at 24 regularly-spaced points (4 locations at each of 6 test ports) across the test duct. Figure 2-5 illustrates the pitot measurement locations. They then installed the pitot at a fixed location which best represented the flow (designated "3c") and recorded ΔP and temperature readings during each test run.

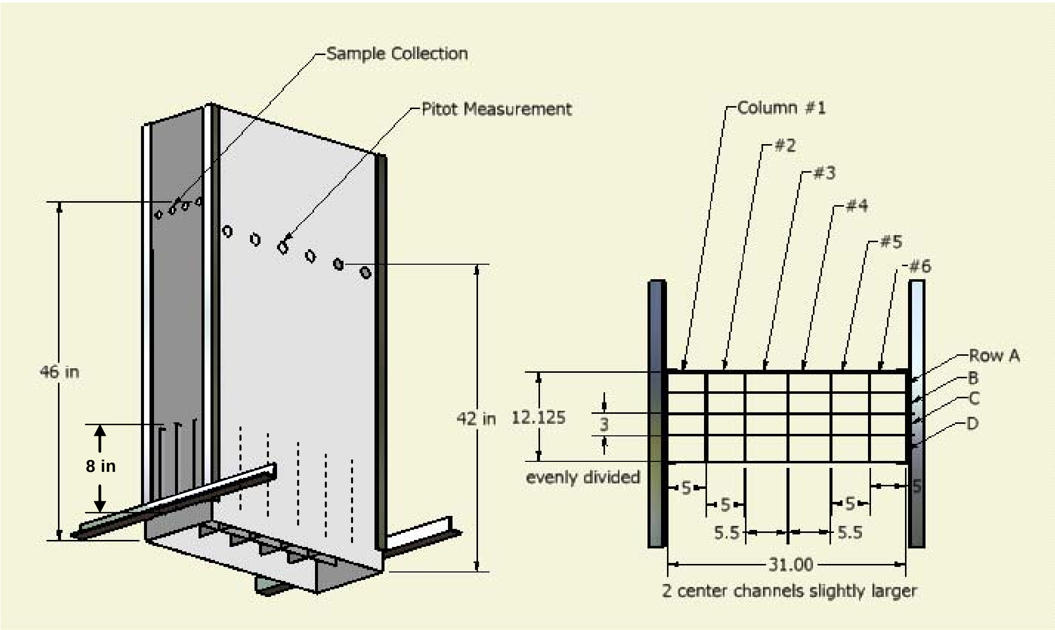


Figure 2-5. Method 2 Traverse Locations

Volumetric flow is proportional to the mean of the square root of the pitot ΔP. Figure 2-6 shows the volumetric flow data from the traverses as a function of the square root of ΔP at point 3c. The correlation coefficient (R^2) of 0.9966 indicates that the square root of ΔP at point 3c is a good predictor of total stack gas flow. The 95 percent confidence interval for flow, as predicted from a ΔP reading at 3c at every notch, is approximately 2.2 percent.

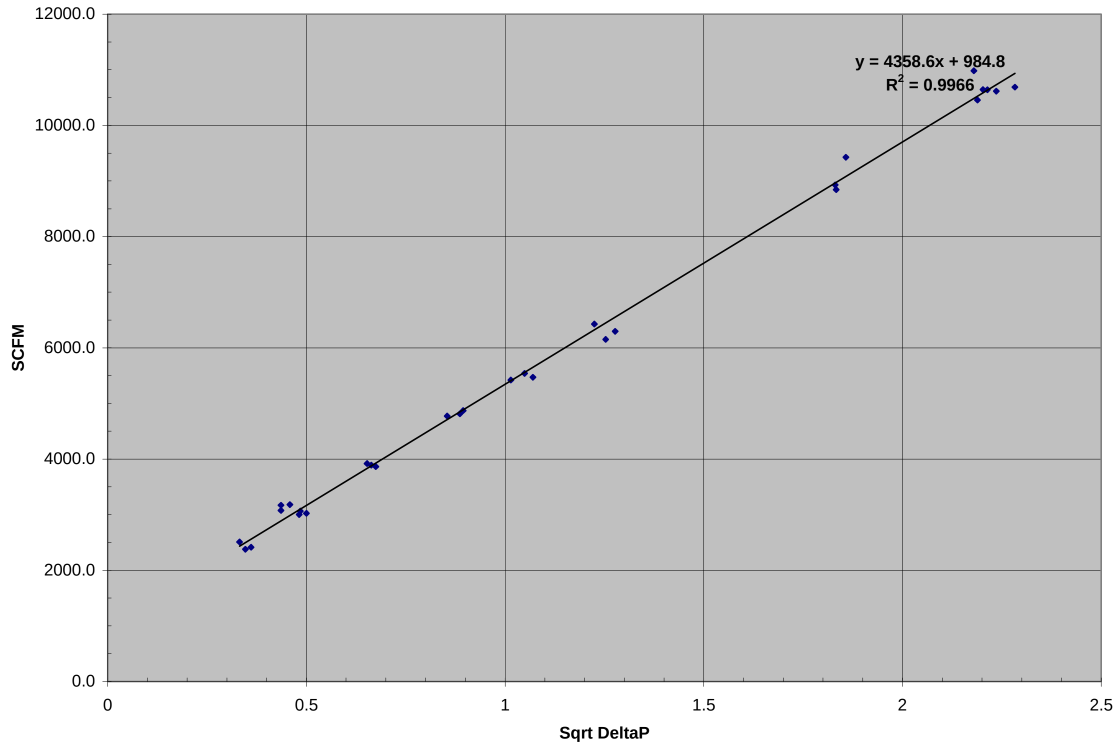


Figure 2-6. Exhaust Gas Volumetric Flow Rate as a Function of $\sqrt{\Delta P}$ at Point 3c

2.2.2. Fuel Meter Results

The fuel meters did not perform as anticipated. Their response changed unpredictably during the August 21 through October 23, 2004 break-in period. This was particularly evident while the locomotive was idling. At idle, the maximum amount of fuel (approximately 380 gph) passed through both meters with a small amount being drawn off by the engine. The meters reported net idle fuel consumption as varying randomly between 17.5 gph and -16.4 gph over the break-in period. This indicates that the idle and low notch data from these meters are invalid and the results at the higher notches have large unquantified inaccuracies, over and above calibration and random sampling error.

The manufacturer's sales literature stated that accuracy on the net fuel consumption would be ± 1.0 percent. Actual absolute compounded accuracy for the meters alone, as documented by the pre-test calibration certificates, was ± 0.80 gph. The fuel meters alone would have met the ± 1.0 percent specification only at net fuel consumption rates greater than 80 gph, or at notch 5 and above for the test locomotive. Overall absolute compounded accuracy (including the datalogger's port accuracy), as documented by the fuel meters' pre- and post-test calibrations was ± 2.04 gph for the baseline tests and ± 2.99 gph for the treated fuel. Compounded absolute accuracy of the net fuel consumption was 3.62 gph, not including sampling error.

GHG Center analysts undertook an extensive review of the pre- and post-test fuel meter calibrations to see if the calibration changes could be corrected, but this proved to be impossible. For example, the as-reported post-test calibrations showed significant changes in the return fuel meter, both in overall accuracy and the trend (or slope) at each calibration point. The changes profoundly affected the treated fuel test results. Also, between the end of the test runs and the calibration exercise, test personnel:

- dismounted both meters from the locomotive
- shipped them to the GHG Center
- performed bench-top evaluations
- shipped the meters to the calibration facility

Calibration facility operators then passed an unknown quantity of clean calibration fluid through the meters. All of this means that the calibration changes during the actual tests are completely unknown at all notches and could have been much larger (or smaller).

Figure 2-7 illustrates how the meters' documented accuracy affected the net fuel consumption results. The BSFC change would have to be larger than the random sampling error compounded with the two meters' calibration error to show statistical significance. This amounts to about 17.0 percent at notch 2 or 4.0 percent at notch 7 and means that it was impossible to quantify small changes in net fuel consumption with the fuel meters.

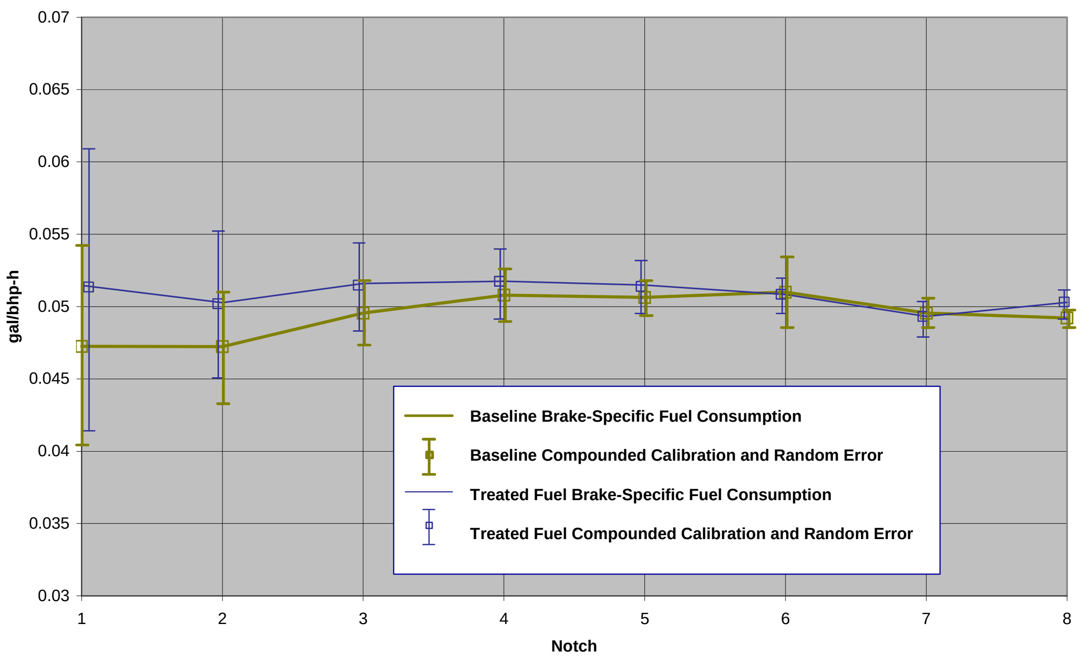


Figure 2-7. Effects of Fuel Meter Calibration Error

The manufacturer calibrated the fuel meter digital outputs at multiple fuel flows and temperatures. The calibration, however, does not document the correspondence of the calibration flow rates with the meters' analog outputs. This means that the analog outputs, as recorded by the GHG Center's datalogger, cannot be shown to have a traceable link to the multipoint calibration procedure.

GHG Center analysts therefore invalidated the fuel meter data and used the carbon balance method to calculate fuel consumption.

2.3. LOCOMOTIVE EMISSIONS

The following tables present the emissions test results.

Table 2-10. Mean Baseline Emissions, grams per minute (g/min)

Pollutant	Lo Idle	Hi Idle	Notch 1	Notch 2	Notch 3	Notch 4	Notch 5	Notch 6	Notch 7	Notch 8
CO	4.9	5.9	4.9	5.4	14.3	38	82	130	100	49.0
s_{n-1}	0.6	0.6	0.7	0.4	0.8	4	17	20	30	1.8
CO_2	630	760	3100	5030	8800	11200	14300	20800	22400	22500
s_{n-1}	110	60	200	130	500	400	300	1200	800	800
NO_X	17.0	19	64	98	150	185	226	380	440	460
s_{n-1}	1.6	3	6	5	10	7	9	20	40	30
THC	1.3	1.6	1.6	2.3	3.9	4.3	5.2	9.2	10.8	10.6
s_{n-1}	0.3	0.2	0.1	0.6	1.8	0.3	0.3	0.6	0.6	0.8
TPM	0.20	0.26	0.77	1.3	3.7	5.0	6.6	8.7	8.5	8.7
s_{n-1}	0.07	0.07	0.12	0.2	0.4	0.6	0.8	1.4	1.1	1.3

Table 2-11. Mean Treated Fuel Emissions, g/min

Pollutant	Lo Idle	Hi Idle	Notch 1	Notch 2	Notch 3	Notch 4	Notch 5	Notch 6	Notch 7	Notch 8
CO	3.3	4.1	3.4	4.0	9.6	20	52	93	54	24
s_{n-1}	0.5	0.3	0.2	0.4	1.2	2	5	17	13	4
CO_2	710	770	2900	4700	7900	10400	13900	19200	22500	22500
s_{n-1}	30	40	180	200	200	300	600	1000	1100	1000
NO_X	16.2	17.2	63	95	136	177	231	377	460	449
s_{n-1}	0.8	0.9	4	10	7	8	8	16	14	14
THC	1.1	1.3	1.11	1.6	2.24	3.3	4.8	7.7	9.1	8.6
s_{n-1}	0.3	0.3	0.11	0.3	0.15	0.4	0.5	0.7	1.1	1.1
TPM	0.29	0.31	1.1	2.2	5.5	7.5	10.5	16	22	23
s_{n-1}	0.15	0.10	0.3	0.3	0.6	0.7	1.1	2	3	3

Table 2-12. Mean Baseline Brake-Specific Emissions, g/bhp-h

Pollutant	Notch 1	Notch 2	Notch 3	Notch 4	Notch 5	Notch 6	Notch 7	Notch 8
CO	1.02	0.65	0.99	1.99	3.2	3.6	2.3	0.99
s_{n-1}	0.16	0.06	0.06	0.19	0.7	0.8	0.7	0.04
CO_2	650	601	610	580	551	580	502	455
s_{n-1}	50	17	30	20	13	60	17	16
NO_X	13.3	11.8	10.4	9.6	8.7	10.6	9.8	9.3
s_{n-1}	1.4	0.8	0.7	0.4	0.4	1.0	0.9	0.5
THC	0.34	0.28	0.27	0.222	0.200	1.257	0.243	0.214
s_{n-1}	0.03	0.07	0.13	0.018	0.011	0.012	0.011	0.015
TPM	0.16	0.15	0.24	0.26	0.26	0.25	0.19	0.18
s_{n-1}	0.02	0.03	0.03	0.03	0.03	0.05	0.02	0.03

Table 2-13. Mean Treated Fuel Brake-Specific Emissions, g/bhp-h

Pollutant	Notch 1	Notch 2	Notch 3	Notch 4	Notch 5	Notch 6	Notch 7	Notch 8
CO	0.69	0.45	0.63	0.99	1.9	2.4	1.1	0.49
s_{n-1}	0.07	0.06	0.07	0.10	0.2	0.5	0.3	0.08
CO_2	590	524	519	507	500	500	470	460
s_{n-1}	30	19	15	21	30	30	20	20
NO_X	11.8	10.7	8.9	8.7	8.4	9.8	9.6	9.3
s_{n-1}	0.6	0.7	0.3	0.3	0.4	0.5	0.3	0.3
THC	0.23	0.18	0.147	0.16	0.17	0.20	0.19	0.18
s_{n-1}	0.03	0.03	0.013	0.02	0.02	0.02	0.02	0.02
TPM	0.24	0.23	0.36	0.37	0.38	0.42	0.47	0.47
s_{n-1}	0.05	0.03	0.03	0.03	0.04	0.06	0.06	0.07

Table 2-14. Mean Line-haul Duty Cycle-Weighted Emissions, g/bhp-h					
Emission	**CO**	**CO_2**	**NO_X**	**THC**	**TPM**
Baseline	1.71	520	10.2	0.27	0.22
s_{n-1}	0.08	10	0.5	0.02	0.02
Treated	0.96	497	9.7	0.21	0.45
s_{n-1}	0.13	18	0.3	0.03	0.06

Table 2-15 Mean Switch Duty Cycle-Weighted Emissions, g/bhp-h					
Emission	**CO**	**CO_2**	**NO_X**	**THC**	**TPM**
Baseline	2.4	660	12.6	0.42	0.259
s_{n-1}	0.3	20	0.8	0.06	0.012
Treated	1.45	600	11.4	0.31	0.38
s_{n-1}	0.12	20	0.4	0.06	0.04

Tables 2-13 and 2-14 incorporate analyzer data from 6 runs for the baseline fuel and 5 runs from the treated fuel. The treated fuel results omit notch 1 data from Run 4 because of instrumental analyzer problems. The tables incorporate TPM data from 4 baseline and 5 treated fuel runs, respectively. Test operators mis-handled filters for baseline run 3, high idle; run 6, notch 1 and notch 2; and treated fuel run 2, notch 1 and notch 2. This means that the duty cycle-weighted results for these runs are not valid.

Figures 2-8, 2-9, and 2-10 show the mean 3-second peak, 30-second peak, and steady state opacity or smoke emissions. Opacity is the amount of ambient light which is blocked by the exhaust plume.

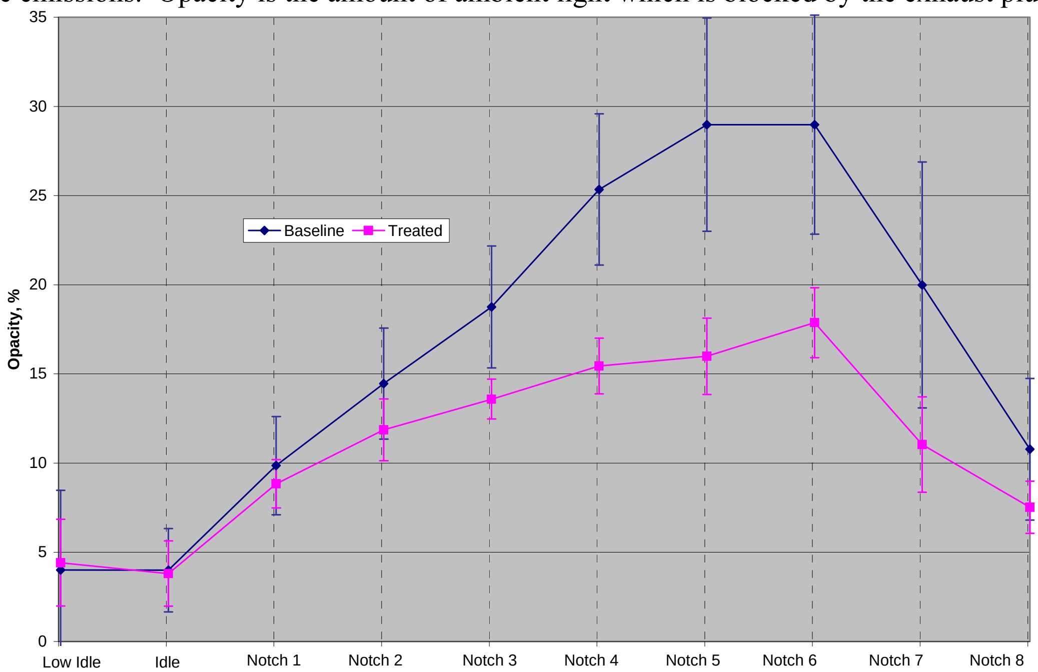


Figure 2-8. Mean 3-second Peak Opacity

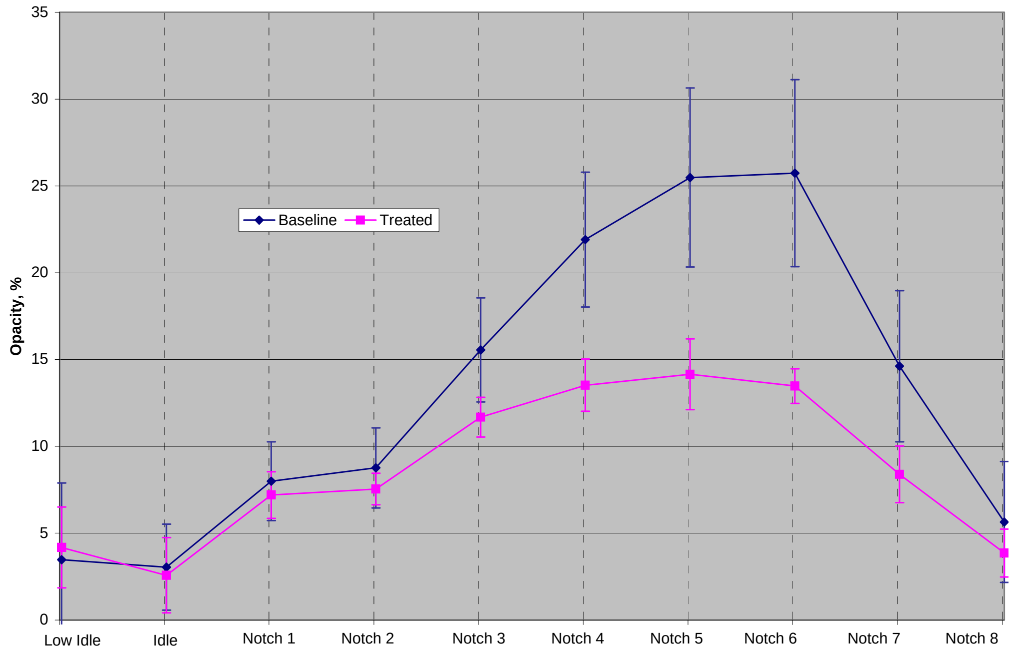


Figure 2-9. Mean 30-second Peak Opacity

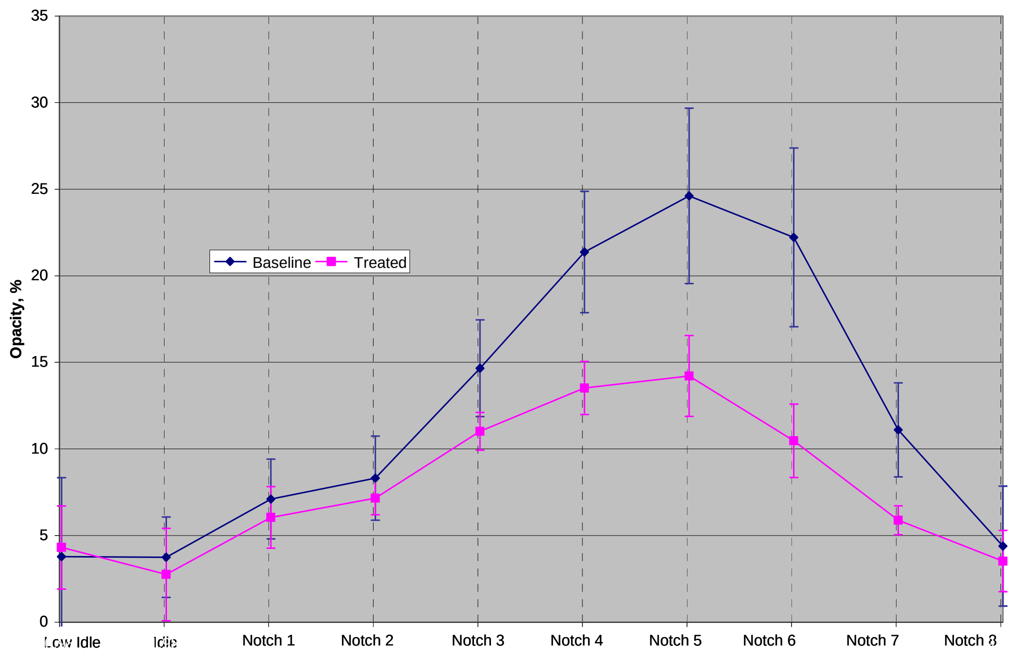


Figure 2-10. Mean Steady-State Opacity

Tables 2-15 through 2-17 provide the opacity numerical results.

Table 2-16. Mean 3-second Peak Opacity

Notch	Lo Idle	Hi Idle	1	2	3	4	5	6	7	8
Baseline%	4	4	10	14	19	25	29	29	20	11
s_{n-1}	4	2	3	3	3	4	6	6	7	4
Treated%	4	4	8.8	11.9	13.6	15.4	16	18	11	7.5
s_{n-1}	2	2	1.4	1.7	1.1	1.6	2	2	3	1.5

Table 2-17. Mean 30-second Peak Opacity										
Notch	Lo Idle	Hi Idle	1	2	3	4	5	6	7	8
Baseline%	3	3	8	9	16	22	25	26	15	6
s_{n-1}	4	2	2	2	3	4	5	5	4	3
Treated%	4	3	7.2	7.5	11.7	13.5	14	13.5	8.4	3.9
s_{n-1}	2	2	1.3	.9	1.1	1.5	2	1.0	1.6	1.4

Table 2-18. Mean Steady-State Opacity										
Notch	Lo Idle	Hi Idle	1	2	3	4	5	6	7	8
Baseline%	4	4	7	8	15	21	25	22	11	4
s_{n-1}	5	2	2	2	3	4	5	5	3	3
Treated%	4	3	6.0	7.2	11.0	13.5	14	10	5.9	3.5
s_{n-1}	2	3	1.8	1.0	1.1	1.5	2	2	0.8	1.8

Mean SO_2 emissions at notch 8 were 0.48 and 0.72 g/bhp-h for the baseline and treated fuel, respectively. The difference was statistically significant, but is based on a limited number of samples. Analysts provided results for three of the baseline runs and two of the treated fuel runs. The increase amounted to 0.24 ± 0.19 g/bhp-h.

Mean SO_4 (sulfate) emissions were 0.007 and 0.009 g/bhp-h for the baseline and treated fuel, respectively, based on three analyses each. The difference was not statistically significant. This report includes these SO_2 and SO_4 results for information only. The SO_2 increase reported here may merit further analysis because it was highly unlikely that fuel sulfur or other properties changed. As explained above, the supplier lifted all fuel from the same lot during the test campaign. Also, Envirofuels has stated that the catalyzer contains no sulfur compounds, so it is difficult to account for the apparent SO_2 emissions increases.

2.4. TPM RESULTS AND ADDITIONAL PARTICULATE ANALYSES

The verification test results show increased TPM emissions while the locomotive was operating on the treated fuel as compared to baseline emissions. Duty cycle-weighted emissions, however, were significantly less than the Tier 0 standards for both fuel conditions. The results are considered valid, but they were unexpected based on the decreased gaseous pollutant, smoke (opacity) emissions, and non-ETV tests performed at other venues.

In an effort to understand the significant TPM emissions increases while observing reductions in all other emissions, the GHG Center and ETC investigated LPSS performance, dilution ratios, and the possible effects of sampling conditions on TPM as related to opacity. Appendix A provides the discussion. EnviroFuels and the GHG Center hypothesized that knowledge of the particulate composition or morphology may help explain whether the reported increase was real, a sampling artifact, or suggest its causes. Elemental verses organic carbon data and other elemental analyses (especially for iron and phosphorus) may also be useful. The GHG Center, therefore, undertook additional analyses of the particulate caught on the TPM filters. These analyses took place about 4 months after the test campaign.

Southern personnel selected notch 5 primary filters from both fuel conditions for analysis. The selected filters most closely represented the overall mean results for THC and TPM. Analytical methods were:

- scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM / EDS) with magnifications of 100x, 300x, and 1000x (by Rocky Mountain Laboratories, Golden, CO)
- X-ray photoelectron spectrometry (XPS, by Rocky Mountain Laboratories)

- SW-846 Method 8270 organic extraction and gas chromatography with mass selective detector (Method 8270 by Enthalpy Analytical, Inc., Durham, NC)

SEM / EDS provided a qualitative assessment of the particle morphology combined with a list of the elements present on the filter (except for H, He, Li, and Be). XPS supplied quantitative elemental data (except for H and He) while Method 8270 yielded an assessment of elemental verses organic carbon.

Results of all the post-test investigations into the cause of the increased TPM emissions were inconclusive.

2.4.1. Particulate Analyses Results

SEM micrographs showed that the particulate loading on the filters was higher for the baseline tests. Table 2-19 presents the relevant filter and test run data for the TPM filters discussed here. Note that only the primary filters were analyzed; the laboratories have archived the backup filters.

Table 2-19. Gravimetric Analyses and Sampling Data

	Filter ID	Description	TPM Mass, mg	Dilution Tunnel Flow, l/m	Dilution Air Flow, l/m	Exhaust Sample Flow, l/m	Dilution Ratio	Sample Flow Rate (at Filter), l/m
SEM / EDS; XPS	082057A	Baseline run 5, notch 5	4.837	448.4	300.2	148.2	3.02	60.1
	102747B	Treated run 4, notch 5	3.915	369.6	303.3	66.3	5.58	54.0
Method 8270	081827A	Baseline run 2, notch 5	5.878	485.3	300.0	185.1	2.62	60.0
	102637B	Treated run 2, notch 5	3.276	360.9	302.8	58.1	6.21	52.8

Table 2-19 shows that the locomotive particulate sampling system dilution ratios varied between the baseline and treated fuels. This is why reported TPM g/h emissions were higher for the treated fuel than for the baseline, even though less particulate mass was caught on the treated fuel filters. The varying volumetric flow rate through the system also led to different sample residence times, ranging between approximately 1.3 and 1.7 s for the baseline and treated fuel, respectively.

Figures 2-11 and 2-12 show the SEM micrographs for the baseline and treated fuel filters. There are no apparent morphological differences, other than that the higher TPM mass on the baseline filter provides more extensive coverage of the filter media.

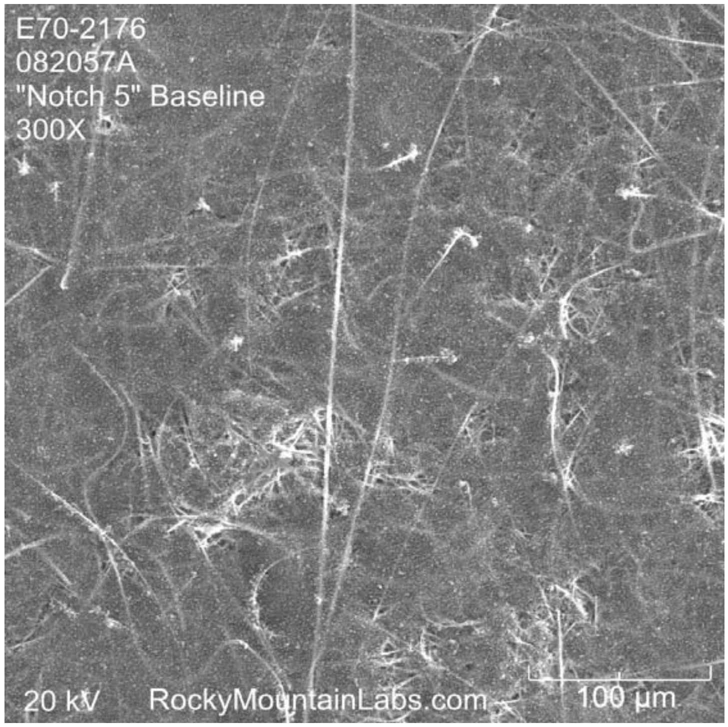


Figure 2-11. Baseline Particulate Filter, SEM Image at 300X

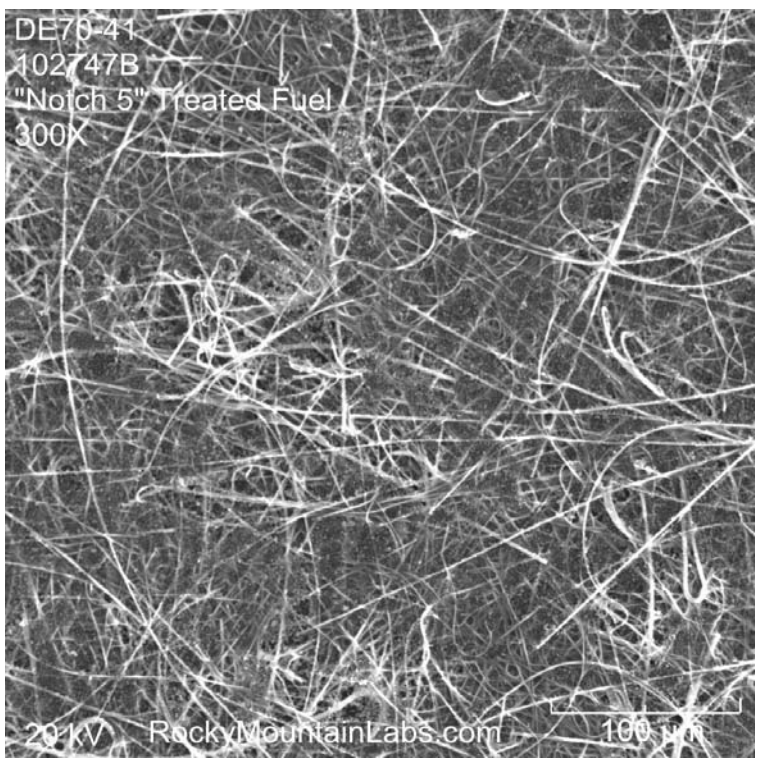


Figure 2-12. Treated Fuel Particulate Filter, SEM Image at 300X

The XPS data included peaks for C, N, O, F, Na, Si, S, and Ca. Fe and P were absent. Figures 2-13 and 2-14 provide the spectrograms and present the data.

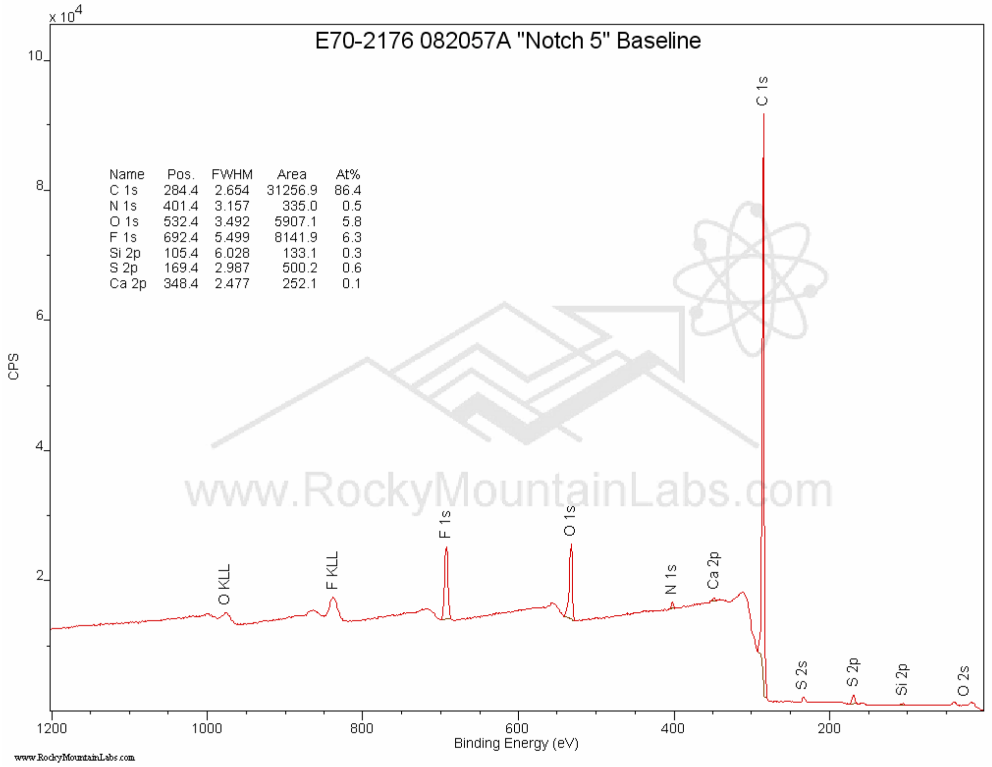


Figure 2-13. Baseline XPS Results

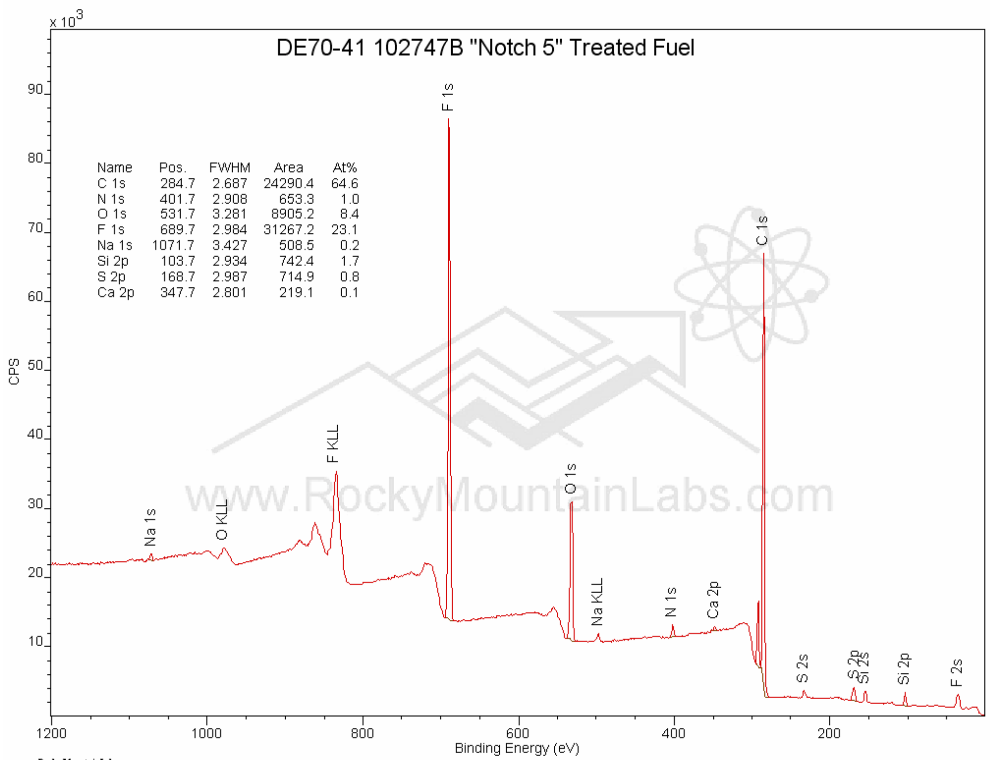


Figure 2-14. Treated Fuel XPS Results

The TPM filter medium was Teflon-bonded borosilicate glass ("Emfab", Pall Corporation). This is the most likely cause of the Si and F indications in the XPS spectrograms. The higher TPM coverage in the baseline filter likely screened the underlying filter fibers, which would lead to the smaller F signal shown in Figure 2-13. Table 2-20 shows the relative C, N, O, Na, S, and Ca concentrations after correcting for Si and F.

Table 2-20. XPS Elemental Concentrations, Corrected for Si and F

	C	N	O	Na	S	Ca
Baseline atom%	92	< 1	6	--	< 1	< 1
Treated atom%	86	1	11	< 1	1	< 1
Baseline weight%	90	< 1	8	--	≈ 1	< 1
Treated weight%	81	1	14	< 1	3	< 1

The elevated S and O in the treated fuel particulate (Table 2-20) could represent increased sulfate deposited on the filter, but not enough to account for the overall TPM increase reported.

Method 8270 showed little change in extractable organic matter between the two fuel conditions on the primary filters. The backup filters were not analyzed. Total hydrocarbons were 0.018 and 0.015 mg, which represented 3.1 and 4.6 percent of the total particulate catch, for the baseline and treated fuel respectively. This implies that, when analyzed, most of the TPM on the primary filters was pure carbon. It is unknown, however, whether deposited organic compounds may have volatilized during the period (about 4 months) between sampling and the 8270 analysis. In one study [6], for example, analysts immediately stored particulate filters in a freezer, handled, and analyzed them under yellow light to reduce volatilization and oxidation. This was not done for the verification tests, although all filters were refrigerated after the gravimetric analyses. The proportion of organics deposited on the primary filter, as compared to the backup filters (which were not analyzed) may also have varied. Recent work [7] has shown that this proportion can vary due to filter media selection.

3.0 DATA QUALITY

The GHG Center selects methodologies and instruments for all ETV verifications to ensure a stated level of data quality in the final results. The test plan described these data quality objectives (DQOs). The test plan also listed contributing measurements, their accuracy requirements, QA/QC checks, and other data quality indicators (DQIs) that, if met, would ensure achievement of the DQOs.

Section 2.5 of the test plan and 2.0 of this report discussed the differences between the Title 40 CFR 92 Subpart B FTP and the field activities. The differences are significant but they have no impact on these baseline - to - treated fuel comparisons because test personnel used identical methods and equipment for each test series. Test activities met all the requirements listed in the test plan, with the exception of the FuelCom fuel meter performance (See Section 2.2.2). This invalidated the direct fuel consumption measurements required by the test plan. Also, substitution of the Method 2 traverses and carbon balance method for the fuel meters departed from the Locomotive FTP. This portion of the field tests therefore did not meet the test plan's DQO that all field activities would conform to the FTP requirements for locomotive emissions determinations except as noted. See the discussion following Table 3-1 for the relevant citations.

The test plan also proposed implicit DQOs that the data show statistical significance, variance similarity, and that the 95 percent confidence interval be refined as much as possible up to a maximum of 6 test runs. Early in the test campaign, the field team leader determined that 6 test runs for each fuel condition would be required to meet these goals, and he scheduled field activities accordingly. The results presented in Section 2.1 showed achievement of statistical significance for all parameters except for:

Parameter	Notch
BSFC	1, 8
Brake-specific CO_2	1, 8
Brake-specific NO_X	1, 5, 6, 7, 8
Brake-specific THC	3

Variance similarity could not be shown for the following cases:

Parameter	Notch
BSFC	3
Brake-specific CO	5, 7
Brake-specific NO_X	3, 7
Brake-specific THC	3
Brake-specific TPM	7, 8

In these instances, analysts applied Satterthwaite's approximation [8] to calculate a revised T distribution value. They then compared T_{test} to the revised T distribution value to determine statistical significance and to calculate the confidence interval.

The following activities and procedures supported the achievement of this verification's objectives:

- on-site QA/QC checks to reconcile the achieved DQIs with the DQOs
- audit of data quality
- on-site performance evaluation audit
- on-site technical systems audit

The following subsections describe reconciliation of the DQIs with the DQOs, the QA/QC checks, and audits.

3.1. RECONCILIATION OF DQOS AND DQIS

A fundamental component of all ETV verifications is the reconciliation of the collected data and their DQIs with the DQOs. For this verification, assessment of the qualitative DQO consists of evaluation of whether the stated methods were followed, if the measurement instruments met the proper specifications, and if the QA/QC checks and calibrations described in the test plan yielded satisfactory results. Achievement of these DQIs implies that the DQOs were met. The following tables show the DQI data for the test campaign. The achieved instrument accuracies provided in Table 3-1 are primarily the result of multipoint laboratory calibrations performed on the individual instrument.

Table 3-1. Instrument Accuracy

Measurement Variable	Observed Operating Range	Instrument Range	Specification	Results	How Verified / Determined
Main traction generator voltage	0 - 840 V	0 - 1000 V	± 0.25% FS	± 0.056% of point (sensor only), ± 0.84% total[a]	Factory calibration
Main traction generator current	0 - 2470 A	0 - 4000 A	± 1.0% of point	± 0.048% of point (sensor only), ± 1.10% total[a]	
Fuel flow rate[b]	220 - 380 gph	50 - 500 gph	± 1.0% of point for differential flow rates	Baseline: ± 0.52% to ± 5.64% of point Treated: ± 1.53% to ± 15.0% of point	Factory calibration
Exhaust gas flow rate *via* Method 2	2400 - 10700 scfm	n/a	± 5.5% [9]	< ± 5.5%	Factory / laboratory calibration
DOES2 main flowrate	50 - 60 lpm	0 - 100 lpm	± 1.0% FS	Baseline: ± 0.86% Treated: ± 0.25%	Factory / laboratory calibration
DOES2 dilution air flowrate	40 - 55 lpm	0 - 100 lpm	± 1.0% FS	Baseline: ± 0.72% Treated: ± 0.28%	
DOES2 analyzer sample flowrate	3 - 4 lpm	0 - 5 lpm, each 10 lpm, total	± 1.0% FS	Baseline: ± 0.93% Treated: ± 0.62%	
LPSS main flowrate	350 - 450 lpm	0 - 8500 lpm	± 1.0% FS	± 1.0% FS	
LPSS dilution air flowrate	298 - 305 lpm	0 - 500 lpm	± 1.0% FS	± 1.0% FS	
Temperature LPSS main	110 - 140 °F	32 - 392 °F	± 0.9 °F	± 0.1 °F	
Diff. pressure, LPSS/DOES	not used	0 - 10 " H_2O	± 0.5% FS	not used	
Ambient temperature	35 - 85 °F	39 - 212 °F	± 0.2% FS	± 0.13% FS	Factory calibration
Ambient pressure	14.4 - 14.8 psia	0 - 15 psia	± 0.25% FS	± 0.01% FS	Factory / laboratory calibration
Humidity, ambient	20 - 100% RH	0 - 100% RH	± 1.0% FS	± 0.5% FS	Factory calibration
CO	0 - 50 ppmv: < 50 ppmv[c] 0 - 300 ppmv: < 300 ppmv[c]	0 - 50 ppmv, Lo Idle to Notch 4; 0 - 300 ppmv, Notch 5 to Notch 8	± 1.0% of point	0 - 50 ppmv: Baseline: ± 0.21% Treated: ± 0.24% 0 - 300 ppmv: Baseline: ± 0.15% Treated: ± 0.25%	Factory, laboratory, field calibration and drift checks

Table 3-1. Instrument Accuracy					
Measurement Variable	**Observed Operating Range**	**Instrument Range**	**Specification**	**Results**	**How Verified / Determined**
CO_2	< 0 - 3.0%[c]	0 - 3.0%	± 1.0% of point	Baseline: ± 0.22% Treated: ± 0.22%	Factory, laboratory, field calibration and drift checks
NO_X	0 - 100 ppmv: < 100 ppmv[c] 0 - 300 ppmv: < 300 ppmv[c]	0 - 100 ppmv, Lo Idle to Notch 1; 0 - 300 ppmv, Notch 2 to Notch 8	± 1.0% of point	0 - 100 ppmv: Baseline: ± 0.15% Treated: ± 0.24% 0 - 300 ppmv: Baseline: ± 0.15% Treated: ± 0.25%	Factory, laboratory, field calibration and drift checks
THC	< 30 ppmv[c]	0 - 30 ppmv	± 1.0% of point	Baseline: ± 0.18% Treated: ± 0.26%	Factory, laboratory, field calibration and drift checks
PM Mass	0 - 6 mg	0 - 2000 mg	± 20 ug precision (std. deviation)	± 5.7 ug std. deviation	Daily calibration
Opacity	0 - 30%	0 - 100%	± 1.0%	± 0.7%	Standard filters

[a]Includes both sensor error and datalogger analog / digital conversion error
[b]The fuel meters did not perform satisfactorily. See Sections 2.2.1 and 2.2.2.
[c]Analyzer operating ranges as observed while sampling diluted exhaust emissions

The test results for fuel consumption are based on Method 2 velocity traverses and the carbon balance method. 40 CFR 92.114(3)(1) allows this through references to Title 40 CFR 86, Subpart N [5]. The Method 2 traverses showed a sampling variability of approximately ± 2.2 percent as discussed in Section 2.2.2. Table 3-1 reports overall Method 2 accuracy as better than 5.5% because the achieved accuracy of each individual measurement exceeded the method requirements [9]. This compares favorably with the measurement methods specified in §86.1319(4). For example, the 40 CFR 86 flow metering element accuracy specification is ± 5.0 percent alone, not including barometric pressure, temperature, or other instrument accuracies. This means that the Method 2 traverses, with accuracies similar to the 40 CFR 86 methods, are a reasonable substitute for the direct fuel consumption measurements. Specifications and accuracies for all other instruments, such as the gaseous analyzers, were either identical to or significantly exceeded those required for the 40 CFR 86 methods.

Table 3-2. Calibrations				
System or Parameter	**Description/ Procedure**	**Date Performed**	**Date Required**	**OK?**
Main traction generator voltage	NIST-traceable calibration with as-found data	07/09/2004	Within 18 months of test	√
Main traction generator current	NIST-traceable calibration with as-found data	07/09/2004	Within 18 months of test	√
DOES2 main flowrate DOES2 dilution air flowrate DOES2 analyzer sample flowrate	Calibration against Gilibrator standard bubble flow meter or Drycal piston-type calibrator	Baseline: 07/19/2004 Treated: 10/19/2004	Immediately prior to travel	√
LPSS main flowrate	Calibration against Meriam laminar flow element	Baseline: 08/04/2004 Treated: 10/19/2004	Immediately prior to travel	√
LPSS dilution air flowrate	Calibration against Gold seal mass flow controller	Baseline: 08/04/2004 Treated: 10/19/2004	Immediately prior to travel	√
Temperature LPSS main	Calibration against Omega temperature calibrator	10/21/2004	Immediately prior to travel	√

Table 3-2. Calibrations				
System or Parameter	**Description/ Procedure**	**Date Performed**	**Date Required**	**OK?**
Diff. Pressure, LPSS/DOES	Calibration against Druck pressure calibrator	not used		n/a
Temperature, ambient	Calibrated against laboratory standard	02/23/2004	Annually	√
Pressure, ambient (BP)	Calibration against Druck pressure calibrator	10/19/2004	Immediately prior to travel	√
Humidity, ambient	Calibrated against laboratory standard	02/23/2004	Annually	√
CO	Gas divider calibration with protocol calibration gases at 11 points evenly spaced throughout span (including zero)	Baseline: 07/07/2004 Treated: 10/18/2004	Every 4 weeks or before analyzer leaves for field	√
CO2				
NOX		Baseline: 07/27/2004 Treated: 09/22/2004		√
THC		Baseline: 07/08/2004 Treated: 10/18/2004		√
CO	CO_2 interference check	Baseline: 07/07/2004 Treated: 10/18/2004	Monthly	√
CO	Water interference check			√
CO_2	Water interference check			√
NO_X	Converter efficiency check	Baseline: 07/07/2004 Treated: 09/22/2004		√
PM mass	Balance calibrated by control weights	Daily	Daily	√
smoke	calibration with NIST traceable ND filters at 0, 10, 20, 40% opacity	08/17/2004	within 6 months of test	√

Table 3-3 QA/QC Check Results				
System or Parameter	**QA/QC Check**	**When Performed/ Frequency**	**Achieved**	**Allowable Result**
Main traction generator voltage	Meter reasonableness check vs. digital voltmeter (DVM)	Performed prior to and during test series	All within ± 0.9% of FS	V values within ± 2.0% of FS
Main traction generator power	Reasonableness: voltage and current within manufacturer's specifications		All logged data within ≈ ± 4.3% of onboard digital control[a]	Power within 10% of nominal for notch
Test duct cyclonic flow	Method 1 cyclonic flow determination	Prior to first test run	mean = 5.1^o cyclonic flow	< 20^o cyclonic flow
Exhaust gas flow rate	Exhaust gas delta P monitoring with stationary pitot at representative sampling location	Throughout all test runs	Maximum error relative to the mean delta P was ± 4.4%	Within ± 15% of the mean Method 2 delta P at that traverse point for each notch
DOES2 leak checks	Tunnel is capped and drawn from by main pump	Performed daily prior to test	< 0.5 lpm	< 1 lpm
DOES2 flowrate check	piston-type calibrator comparison	Performed prior to testing	< 1.0% FS	± 1.0% of FS or ± 2.0% of point
LPSS leak checks	Tunnel is capped and drawn from by sample pump	Performed daily prior to test	≤ 6.9 lpm	< 10 lpm

Table 3-3 QA/QC Check Results				
System or Parameter	**QA/QC Check**	**When Performed/ Frequency**	**Achieved**	**Allowable Result**
LPSS flowrate check	Each flow device is removed from the system and compared to a calibrated laminar flow element	Performed prior to travel	< 1.0% FS	± 1.0% of FS or ± 2.0% of point
Temperature LPSS main	Each temperature probe is removed and calibrated against a temperature calibrator.	Performed prior to travel	± 0.6 °C	± 1.7 °C
LPSS / DOES2 moisture condensation	Inspection of filter holders for moisture	Immediately following each test run at each mode	No moisture observed	No visible moisture on the internal surface of any fitting, housing, or filter
Tunnel blank	Run simulation test sequence	One blank taken per day	Blank included in filter analysis; exceeded 5.0%	Include blank in filter analysis if ≥ 5.0% of sample weight
Ambient Pollutant Levels	Disconnect from exhaust probe and run test trace also serves as warm up run.	One sample per test series	Reasonable ambient levels	Reasonable ambient levels
Analyzer zero and span drift check	Analyzer is zeroed and spanned before each reading using on site calibration gases	Each test run	< 2.0% FS	Post-test zero or span drift shall not exceed ± 2.0% FS
[a]Locomotive had been re-engineered for mother / daughter service. Nominal data was not available.				

3.2. AUDITS

The GHG Center's QA manager performed the audit of data quality by randomly selecting at least 10 percent of the data, implementing an independent analysis, and comparing the results to those cited in this report. The QA manager then drafted a report which describes the audit and submitted it directly to the GHG Center director. In general, the audit results were satisfactory.

Robert S. Wright of the EPA Air Pollution Prevention and Control Division and John R. Albritton of the Research Triangle Institute's Center for Energy Technology performed an on-site technical systems audit during the treated fuel test series. This audit's objective was to independently verify that the equipment, procedures, and calibrations were as specified in the test plan. The audit results were satisfactory.

The field team leader conducted a performance evaluation audit of the DOES2 and gaseous emissions analyzers by introducing an audit gas with a known concentration of CO_2 in air to the DOES2 sample train, both at the test duct (which challenged the whole system) and while bypassing the heated umbilical. The system operator knew only that the concentration would be between 0.5 and 4.0 percent CO_2 in air. Table 3-4 provides the results.

Table 3-4. Performance Evaluation Audit				
Date	**Analyzer Response**	**% difference[a]**	**System Response**	**% difference[a]**
08/19/2004			2.10% CO_2	-16.0
10/26/2004	2.10% CO_2	-16.0	1.97% CO_2	-21.2
[a]Audit gas concentration was 2.50% CO_2 in air				

The individual audits represent a single challenge at one concentration, so no statistical inferences may be drawn, but the audit results indicate that the system may have responded with a negative offset during both the baseline and treated fuel tests. The offsets are of similar magnitudes and it can be noted that the difference between the two audits (0.13% CO_2) is less than the standard deviation of CO_2 concentration for most notches. Some examples are as follows:

Table 3-5. Mean CO_2 Concentrations				
	Baseline		Treated	
Notch	**CO_2%**	**s_{n-1}%**	**CO_2%**	**s_{n-1}%**
1	1.93	0.08	1.84	0.10
3	3.34	0.13	3.26	0.12
5	4.37	0.09	4.26	0.22
7	4.35	0.16	4.18	0.22

This means that possible system response differences between the baseline and treated fuels were, in general, similar to or hidden within the observed sample variation. This did not impact the ability to perform the baseline / treated fuel comparisons.

4.0 TECHNICAL AND PERFORMANCE DATA SUPPLIED BY ENVIROFUELS, LP

EnviroFuels, L.P. submitted the contents of this section. They are reproduced in their entirety except for minor changes intended to preserve editorial consistency (formatting, section numbering, etc.). In accordance to ETV program goals, this section provides an opportunity for Envirofuels, LP to respond to the verification results and to provide additional comments, in-house data, anecdotes, or other information regarding the Diesel Fuel Catalyzer, its applications, or effects not addressed elsewhere in this report. The GHG Center did not peer review the vendor's submittal and has not independently verified the statements made in this section. The information presented in this section does not affect the overall verification results.

4.1. TPM DETERMINATIONS

EnviroFuels, L.P. has doubts about the validity of the TPM data reported in this verification because of questions about the LPSS calibrations. This conclusion is based upon the following observations:

1. In several hundred laboratory and field tests of the catalyzer, no case has been observed in which the particulate increased concomitant with a decrease in CO and THC emissions. Such a result would be inconsistent with the chemistry underlying the mechanism of catalyzer effectiveness.

2. The opacity measurements, made directly through exhaust stack gas sampling, are consistent with expected TPM decreases which would accompany lower CO and THC treated fuel emissions. The single scattering albedo for black carbon (soot) particles is about 0.5 [10], so substantial amounts of absorption and scattering by soot particles occur. With reference to the opacity measurements, then, it is difficult to conceive of additional particles which would lower the opacity; negative absorption (emission of light) is a physical improbability in this case and negative scattering is without physical meaning.

3. Filters from the ETV testing have been subjected to several tests that have failed to detect additional components of the particulate. SEM / EDS and XPS analyses at Rocky Mountain Laboratories revealed only increased particulate, most of which is soot, on the Notch 5 baseline filters. Less soot occurs on the Notch 5 treated filters, and little difference exists between the other components in the baseline and treated cases. The S content in both cases, for example, is about 0.1 atom% (uncorrected for filter material). Enthalpy, Inc., extracted filter samples from the baseline and treated fuel experiments and subjected the extracts to GC/MS analysis. Those analyses revealed very low percentages of hydrocarbons which similar experiments over the years have shown to be typical components of soot particles from the combustion of carbonaceous fuels [11, 12]. Thus, we have been able to find no evidence for components of the particulate emitted by the catalyzer-treated fuel that are not present in that emitted by the baseline fuel.

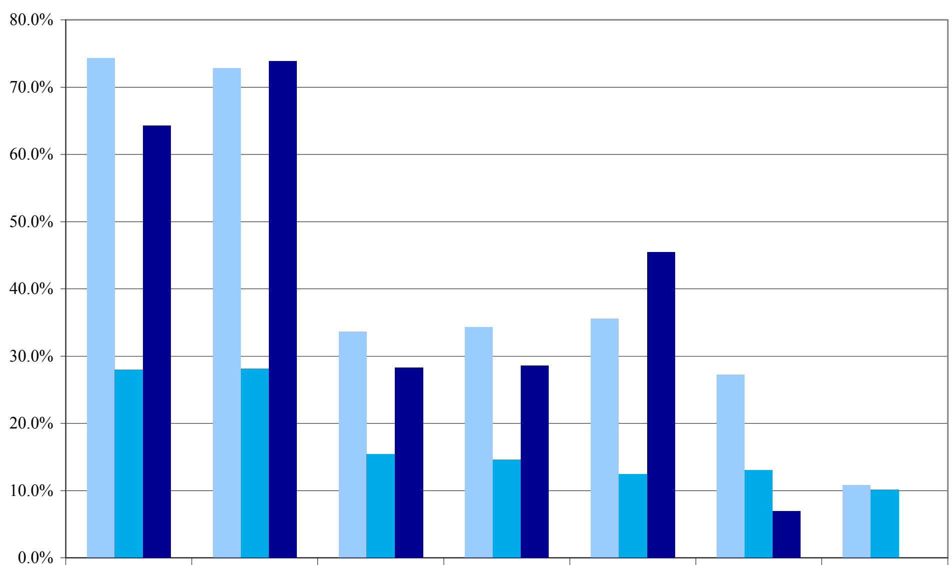
The solution to this dilemma may lie in the determination of TPM with the LPSS. The two different LPSS operators selected significantly different sample dilution ratios for the baseline and treated fuel tests. The reported TPM emissions should not vary with different dilution ratios, assuming the same actual emission rates. EnviroFuels questions this assumption because of the apparent correlation between the TPM and dilution ratios as discussed in Appendix A. Wall effects and sedimentation, functions of aerosol mass density, number density and flow rate, were almost certainly different in the two cases.

Although later laboratory work appears to show no correlation effects (see Appendix A), field conditions varied widely by comparison. Different engine type, size, ambient conditions, and exhaust gas temperatures all may have induced changes in the field-reported TPM emission rates which would not have been observed in the laboratory.

4.2. BASELINE FUEL CONSUMPTION MEASUREMENT FOR NOTCHES 7 AND 8

The EMD engine for the EnviroFuels, L.P. ETV test used mechanical fuel injection. Fuel injection into the cylinders of the engine is a direct function of the RPM of the engine and a mechanically adjusted injector rack setting for each individual fuel injector. The injectors inject approximately the same amount of fuel with each stroke unless the injector rack length is shortened by the electro-hydraulic control system of the engine's governor to reduce the power output of the engine. The governor receives electrical control signals from the locomotive's main generator output control system and controls the rack setting as required to produce the requested power. The governor also balances the rack settings against the electrical system's power limiting parameters and the engine's mechanical limitations.

The engine power output is a direct result of the amount of fuel injected. During baseline testing the engine showed the correlation among the increase in fuel, RPM change and power output change for notches 1 to 7 shown in Figure 4-1. The power increase and RPM increase between notch 7 and notch 8 with no related fuel consumption increase is inconsistent with the operation of this type of EMD engine and cannot be explained.



	2	3	4	5	6	7	8
BHP % Change	74.3%	72.8%	33.6%	34.4%	35.6%	27.2%	10.8%
RPM % Change	28.0%	28.1%	15.4%	14.6%	12.4%	13.1%	10.1%
GPH % Change	64.3%	73.9%	28.3%	28.6%	45.5%	6.9%	0.0%

Notch Setting

Figure 4-1. Baseline Percent Change from Previous Notch

This inconsistency—more power without an increase in fuel consumption under the same conditions—occurred in each of the six baseline runs. Keeping in mind that the engine operated in each notch for at least 6 minutes, the data show that on the same day, typically under the same weather conditions, using the same fuel, the engine's power output increased by ten percent with no change in fuel consumption. It is not possible to explain this change with the data available.

If the notch 8 efficiency was, in fact, the same as notch 7 efficiency, then the reported fuel economy improvement for notch 8 would be approximately 7 percent instead of 0 percent. Similarly, fuel efficiency for the Line Haul Duty Cycle would be approximately 9 percent instead of 5 percent.

5.0 REFERENCES

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Appendix A
Post-Test LPSS Correlations

Introduction

The TPM results in Sections 2.1 and 2.3 showed increased emissions even though all gaseous and visible emissions (smoke opacity) decreased significantly. The results are valid and the increases are reported as real. This is because "mass tends to be conserved during the dilution and sampling process" [A1], but consideration of the factors that could have affected the results is useful.

TPM as Related to Opacity

The increased TPM emissions at lower opacity is of interest. Opacity at higher levels can have a known relationship to particulate emissions if the particle size distribution is known accurately [A2]. The relationship breaks down quickly at low opacity levels [A3], such as those seen during the test campaign, and if the size distribution changes. Fuel sulfur content [A4], sampling conditions such as residence times combined with ultimate dilution ratios [A5, A6, A7], sulfur saturation ratios experienced in the sampling system [A6], and other factors all have synergistic effects on particle size distribution and number. These changes may have affected light scattering and the resultant smoke visibility [A1]. Exhaust gas temperatures, for example, were lower during the treated fuel tests (see Table 2-6), which could have had unknown effects on the collected TPM.

Exhaust Gas and Engine Intake Air Temperature Changes

Many factors, other than use of the fuel catalyzer, could have contributed to the increased TPM emissions. For example, Table 2-6 showed that the exhaust gas and engine intake air temperatures were lower for the treated fuel tests. It is possible that the temperature changes could have affected the particulate emissions, such as by changing condensation behavior. The quantitative effects, however, are unknown.

LPSS Operations

LPSS operations may have introduced sampling artifacts even though the equipment met the DQIs listed in Tables 3-1 through 3-3. Table 2-19 showed that operators used different dilution ratios for the baseline and treated fuel tests. Figure A-1 shows that the LPSS response appears to have changed at different dilution ratios, especially in the higher operating notches. This effect became more pronounced at higher TPM emission rates and lower tunnel flow rates, as shown by the changing slopes of the trend lines.

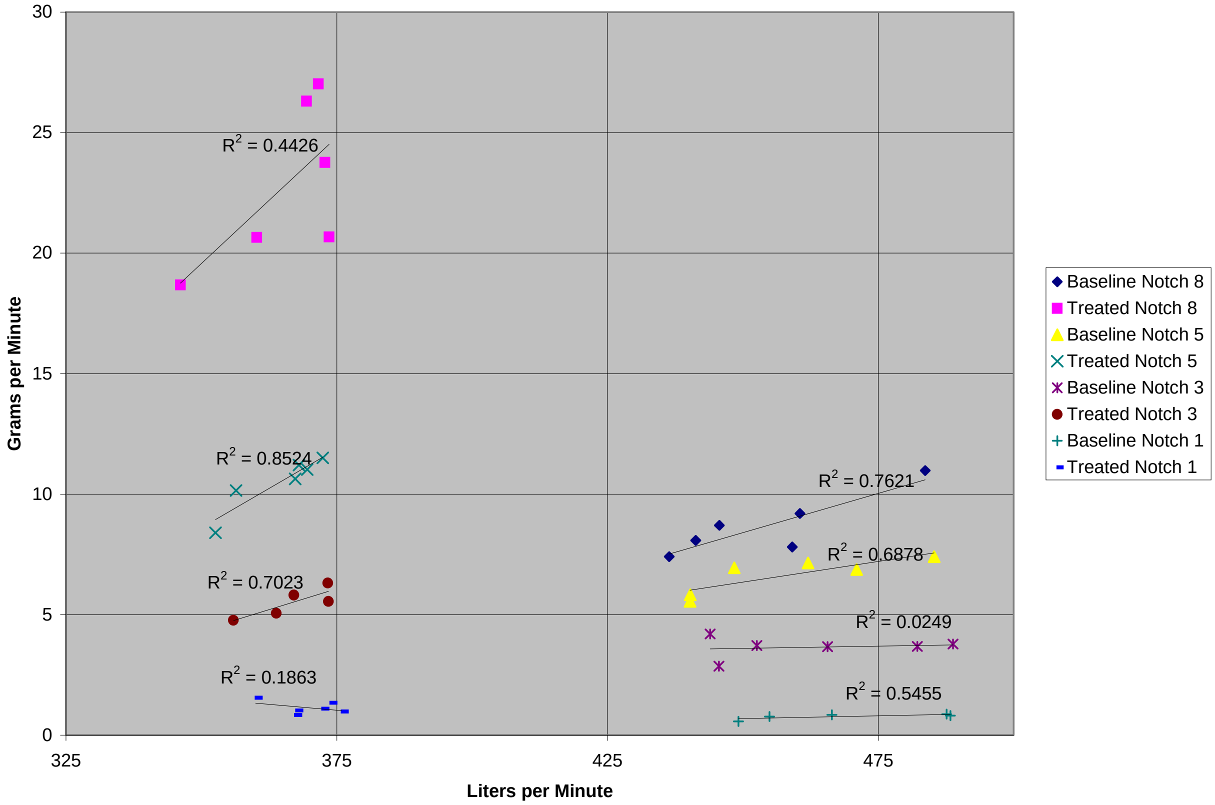

Figure A-1. LPSS Dilution Tunnel Flow verses Reported TPM Emissions

The correlations shown in Figure A-1, however, do not necessarily prove that the changing sample dilution ratios actually caused the reported TPM to change. For example, TPM as reported by the LPSS also appears to be correlated to changing exhaust gas and inlet air temperatures. While the changing LPSS response shown here is not sufficient to invalidate the TPM data, the GHG Center or ETC cannot definitively state whether these are sampling artifacts, effects of engine operations changes, due to other factors, or truly representative of the particulate emissions. Note that ETC performed post-test laboratory comparisons between the LPSS and a constant volume sampling system. The results, quoted below, indicate little correlation between dilution ratios and reported TPM.

As a comparison, gaseous emission rates as reported by the DOES2 appear to have little dependence on the dilution tunnel flow. Figure A-2 shows the DOES2 system response for CO_2.

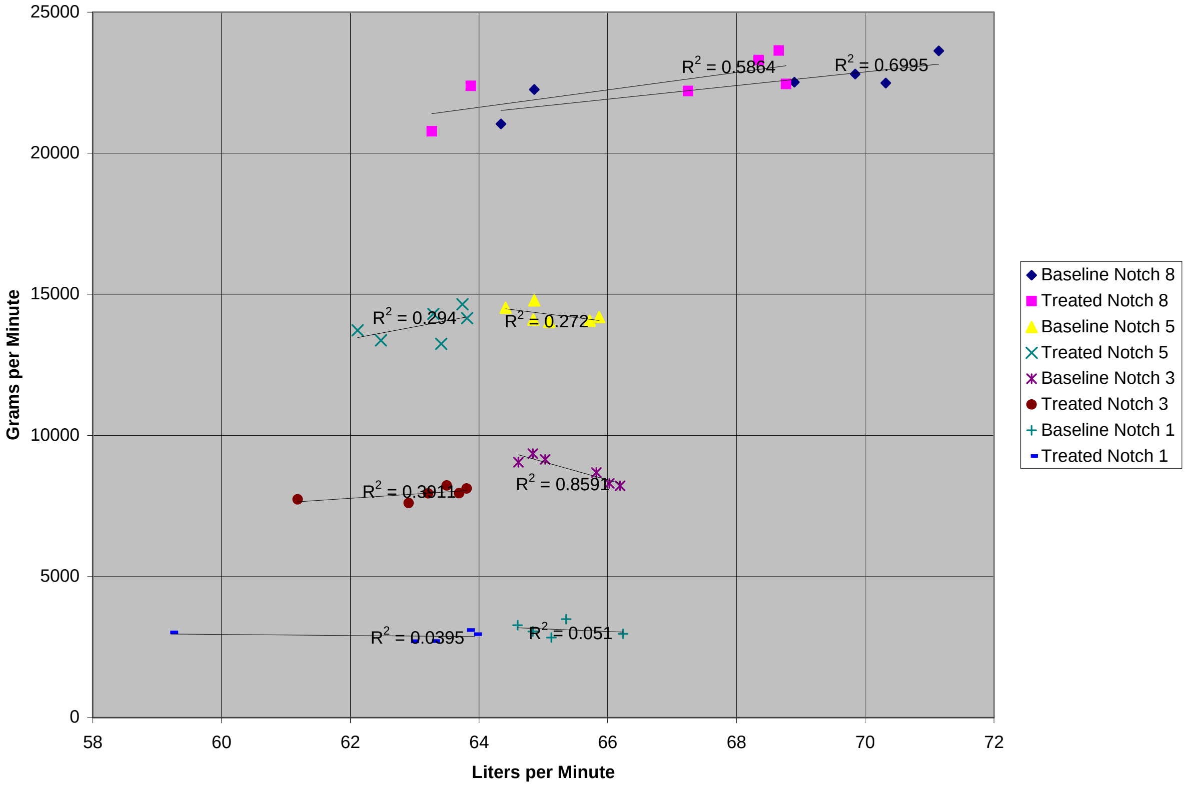

Figure A-2. DOES2 Dilution Tunnel Flow verses Reported CO_2 Emissions

ETC performed a series of correlation studies in response to these concerns. The following memorandum presents the results of the study.

Date: 10.05.2005

Emissions Research and Measurement Division
Environment Canada
Environmental Technology Centre
335 River Road
Ottawa Ontario Canada
K1A 0H3

Greenhouse Gas Technology Center
Southern Research Institute

Attention: Bob Richards

Subject: **Correlation and Validation of the Locomotive Particulate Sampling System (LPSS) Technology**

Dear Sir:

The Emissions Research and Measurement Division's (ERMD) LPSS has recently completed a follow-up cross correlation study comparing the test system used for particulate collection during the locomotive field testing, known as the LPSS, and the ERMD's Heavy Duty Engine Emissions Test Cell #1 (HD cell) which is used to conduct diesel emissions research and technology verifications. This testing was conducted on May 6th 2005.

The LPSS was designed to collect diluted exhaust samples in order to measure total particulate matter (TPM). The HD cell employs constant volume sampling (CVS) which conforms to the Code of Federal Regulations (CFR) Title 40 Part 86. The LPSS was tested in an **"as found"** condition meaning that no calibration settings were altered or verified prior to testing. A leak check was performed prior to the commencement of testing to replicate field procedures. This letter summarizes the observations and results that were obtained from this validation work.

Heavy Duty Cell Correlation

A Mack AI 300A engine running on an ultra low sulfur diesel (ULSD) fuel was used to generate the exhaust emissions for the correlation between the heavy-duty test cell equipment and the LPSS. The engine was tested using a steady state mode with an engine set point of 900rpm and 50% throttle. Double Emfab 70mm filters were used to collect the TPM and these filters were allowed to stabilize in a humidity and temperature controlled room before and after testing. The engine air intake was measured using a 2500 scfm Laminar Flow Element (LFE) in order to calculate the mass emission rate.

Due to the large amount of exhaust the LPSS draws, testing for the LPSS and HD cell does not occur simultaneously so as not to affect the HD cell results used for comparison. Sample collection took place in the following order: HD cell #1, LPSS #1-7, HD cell #2 and #3. Since this study was initiated in order to compare the mass emission rates at different tunnel flow set points, three tests were completed using the same tunnel flow rate as used in the 'Treated' test series during the field testing, followed by three repeats using the same tunnel flow rates as seen in the 'Baseline' testing portion of the field project. A seventh test was performed in order to gather data on a mid range setting in the event that any trends did appear. The following tables present the results of testing.

May 6th, 2005 testing

LPSS Steady State Test Results

Test run ID	LPSS Tunnel flow set point (scfm)	Measured LPSS Tunnel flow (slpm)	Measured LPSS Exhaust flow (slpm)	Engine Air Intake Flow (scfm)	Test Duration (secs)	Mass emission rate g/bhp-hr
LPSS TST #1	13.0	369.72	68.01	190.80	480.00	0.1422
LPSS TST #2	13.0	368.77	67.10	189.40	363.00	0.1295
LPSS TST #3	13.0	369.26	67.55	190.77	360.00	0.1269
LPSS TST #4	17.0	467.67	161.38	191.31	360.00	0.1307
LPSS TST #5	17.0	464.99	158.28	191.31	360.00	0.1264
LPSS TST #6	17.0	464.61	157.03	193.65	360.00	0.1284
LPSS TST #7	14.7	420.98	119.22	192.14	359.00	0.1206
Average						**0.1292**
St dev						0.0066
COV						5.1%

March 9th, 2004 testing

HD Cell Steady State Test results

Test run ID	Total flow through CVS (SCF)	Test Duration (secs)	Mass emission rate g/bhp-hr
HD cell #1	28198	600	0.1223
HD cell #1	13970	300	0.1311
HD cell #1	13967	300	0.1308
Average			**0.1281**
% difference from LPSS			**0.86%**

Note that the% difference = (LPSS- HD cell)/HD cell

Leak Check

Prior to correlation testing a leak check was conducted on the LPSS system including the heated line. The leak check was conducted under a vacuum and showed a leak in the range of 0.41 to 0.25 lpm. This leak check passes the standard set out in the Locomotive test plan.

Recommendations and Observations

1. The mass emission rates stated above do not include a correction for tunnel background. A tunnel blank was taken for the LPSS, however the number exceeded all tunnel blanks seen in the field by three times and therefore it was not considered representative of the sampling conditions seen in the field. It is theorized that the tunnel blank was compromised by the set up procedures and the leak check of the LPSS. During the set-up double filters were not installed thereby allowing particulate to collect on the filter holder. The filter holder was cleaned prior to LPSS

TST #1. Also, no tunnel background was taken for the HD cell and it would not be appropriate to correct one sample for tunnel background and not the other.

2. The LPSS correlated to the Heavy Duty Test cell to within less then a 1% difference when looking at the average mass emission rates of the two test systems.
3. Since the main goal of the correlation testing was to verify whether the tunnel flow rate through the LPSS artificially affects the mass emission rate, it is important to note that when comparing the flow rates at the 13.0 and 17.0 set points, with the corresponding mass emission rates – no trends evolved as seen in the following chart. An ANOVA test was performed and confirmed that there was no statistically significant difference between the mass emission rates at the two set points.

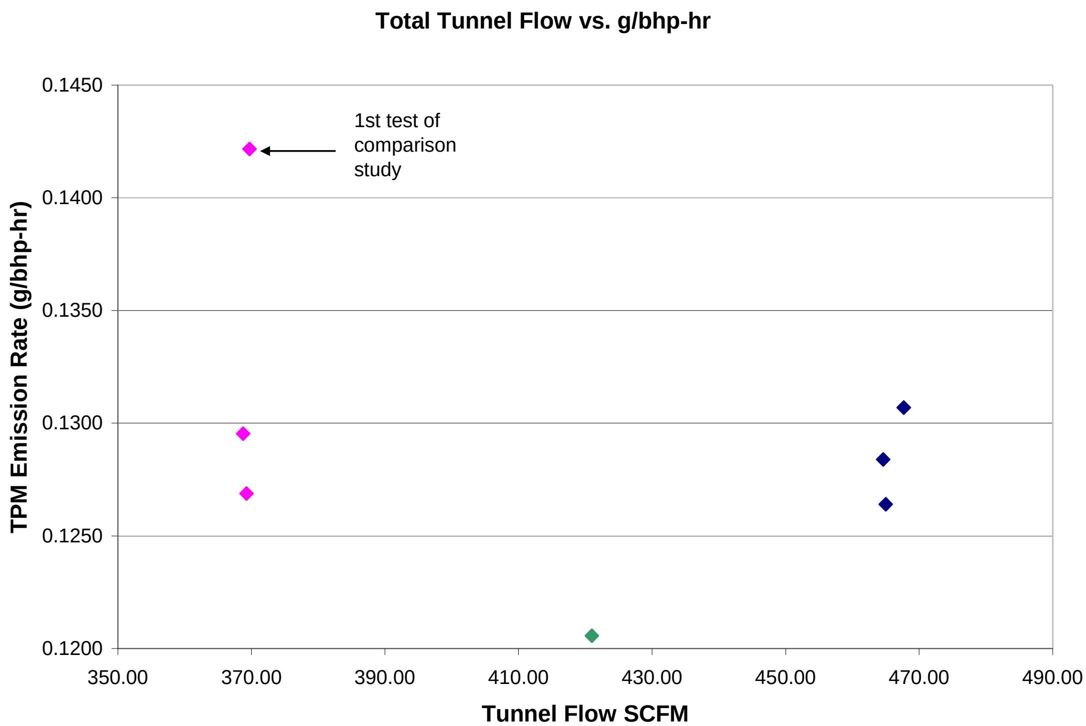

Figure A-3. LPSS Correlation Data

If you require more information, please do not hesitate to contact me.

Sincerely,

Jillian Hendren,
ERMD
Environment Canada

c.c.
Fred Hendren, Chief ERMD
Greg Rideout, Head Toxic Emissions Research & Field Studies, ERMD
Chris Beregszaszy, Project Engineer, Heavy Duty test cell

Appendix A References

[A1] *Engines and Nanoparticles: A Review*, D. B. Kittleson, Ph.D., *Journal of Aerosol Sciences*, Vol. 29, No. 5/6, pp. 575 - 588. 1998

[A2] *Plume Opacity and Particulate Mass Concentration*, Pilat, M. J., Ensor, D. S., *Atmospheric Environment*, Vol. 4, pp. 163-173. 1970

[A3] *Plume Opacity Related to Particle Mass Concentration and Size Distribution*, Thielke, J. F., Pilat, M. J., *Atmospheric Environment*, Vol. 12, pp. 2349-2447. 1978

[A4] *Diesel Fuel Effects on Locomotive Exhaust Emissions*, S. G. Fritz, P.E., T. Brasil, P.E., International Council on Combustion Engines (CIMAC), Paper No. 7A-05, presented at the 23rd CIMAC congress, Hamburg, Germany. 2001

[A5] *Evolution of Particle Number Distribution Near Roadways—Part I: Analysis of Aerosol Dynamics and its Implications for Engine Emission Measurement*, K. M. Zhang, A. S. Wexler, *Atmospheric Environment*, No. 38, pp 6643 - 6653. 2004

[A6] *Review of Diesel Particulate Matter Sampling Methods—Final Report*, D. B. Kittleson, Ph.D., M. Arnold, W. F. Watts, Jr., Ph.D, University of Minnesota, Minneapolis, MN. 1999

[A7] *Particulate Mass Measurements of Heavy-Duty Diesel Engine Exhaust Using 2007 CVS PM Sampling Parallel to QCM and TEOM—Final Report*, I. A. Khalek, Ph.D., U.S. Environmental Protection Agency, Ann Arbor, MI. 2003

Appendix B
Test Run Results

Table B-1. Baseline Fuel Consumption (carbon balance method), gph										
Run / Notch	Lo Idle	Hi Idle	1	2	3	4	5	6	7	8
1	4.10	4.88	19.48	34.73	59.64	73.19	97.72	144.48	150.91	162.36
2	4.36	5.13	20.39	33.35	57.01	75.00	97.13	128.30	147.41	154.51
3	5.15	5.84	22.46	35.73	56.41	78.68	97.08	145.27	159.59	156.75
4	4.52	5.33	20.98	34.85	64.31	77.43	102.24	148.75	153.81	154.76
5	5.01	5.77	23.95	33.59	62.78	77.46	97.41	152.75	162.07	153.00
6	3.02	4.82	21.29	34.70	62.13	80.43	100.46	142.84	152.11	144.60
Mean	4.36	5.30	21.43	34.49	60.38	77.03	98.67	143.73	154.32	154.33
Std Dev	0.77	0.44	1.58	0.88	3.22	2.59	2.16	8.34	5.52	5.78

Table B-2. Treated Fuel Consumption (carbon balance method), gph										
Run / Notch	Lo Idle	Hi Idle	1	2	3	4	5	6	7	8
1	4.63	5.01	18.55	29.75	52.13	70.60	94.50	125.26	143.57	142.44
2	4.85	5.45	20.68	32.46	53.04	69.30	92.04	125.00	155.92	152.31
3	4.68	4.97	18.61	31.24	54.49	73.81	98.56	138.74	157.71	159.82
4	5.00	5.25	N/A	31.86	54.56	72.75	100.94	141.38	163.67	162.13
5	5.23	5.66	20.27	32.49	55.68	72.51	97.44	136.33	159.43	154.03
6	5.03	5.44	21.22	34.38	56.40	67.96	91.17	128.47	147.10	153.52
Mean	4.90	5.30	19.87	32.03	54.38	71.16	95.77	132.53	154.57	154.04
Std Dev	0.23	0.27	1.22	1.54	1.59	2.25	3.84	7.17	7.68	6.88

Table B-3. Baseline bhp								
Run / Notch	1	2	3	4	5	6	7	8
1	290.7	504.3	874.7	1165.6	1568.2	2387.2	2686.8	2971.9
2	292.4	503.4	868.3	1162.0	1551.5	1974.3	2654.1	2970.2
3	288.7	503.9	866.7	1157.2	1559.0	2299.3	2698.5	2973.1
4	282.1	499.8	865.2	1151.7	1557.3	2322.1	2667.4	2964.3
5	285.5	504.5	863.9	1150.2	1551.9	1949.0	2682.3	2938.2
6	286.6	494.4	858.7	1157.9	1536.1	1958.9	2661.9	2951.3
Mean	287.7	501.7	866.3	1157.4	1554.0	2148.5	2675.2	2961.5
Std Dev	3.7	4.0	5.3	5.9	10.6	207.8	16.8	13.9

Table B-4. Treated bhp								
Run / Notch	1	2	3	4	5	6	7	8
1	297.6	531.1	913.8	1229.0	1664.1	2339.0	2889.4	2909.0
2	298.3	529.4	916.3	1224.2	1649.2	2341.8	2877.6	2902.1
3	280.8	524.0	902.6	1214.6	1623.3	2270.8	2822.6	2912.6
4	294.4	526.6	905.8	1217.8	1630.4	2278.7	2882.3	2904.0
5	284.0	522.8	903.6	1218.0	1636.2	2333.7	2877.7	2901.7
6	304.3	577.6	962.5	1254.6	1669.0	2354.2	2869.2	2901.1
Mean	293.2	535.2	917.4	1226.4	1645.4	2319.7	2869.8	2905.1
Std Dev	9.0	21.0	22.8	14.8	18.6	35.6	24.1	4.6

Table B-5. Baseline CO g/m										
Run/Notch	Lo Idle	Hi Idle	1	2	3	4	5	6	7	8
1	3.6833	4.7589	3.5669	4.8299	13.8269	33.6921	51.0595	116.6610	135.9270	48.7499
2	5.2487	5.5454	4.7024	5.1756	14.1493	40.5721	78.3031	110.0549	125.0941	47.1276
3	5.1983	6.2430	4.9505	5.4637	13.2343	35.5568	96.7614	129.6962	75.1477	51.2079
4	5.0392	6.0248	5.1139	5.2686	14.5596	38.5811	92.0241	122.2616	131.4441	48.1980
5	5.2148	6.4966	5.5656	5.5574	14.2929	38.0594	81.3535	164.7529	78.3384	51.1965
6	5.2216	6.3419	5.4401	6.1580	15.5453	43.7638	91.9923	117.4745	73.7032	47.4468
Mean	4.9343	5.9018	4.8899	5.4089	14.2680	38.3709	81.9156	126.8169	103.2758	48.9878
Std Dev	0.617392	0.649988	0.720904	0.446195	0.773856	3.574372	16.67084	19.69553	30.40787	1.806821

Table B-6. Treated CO g/m										
Run/Notch	Lo Idle	Hi Idle	1	2	3	4	5	6	7	8
1	4.2791	4.4962	3.4194	3.3822	8.3766	17.9507	49.9118	76.9784	39.2637	17.4043
2	2.9453	3.8042	3.0084	3.7385	8.1492	18.7042	49.8591	86.8480	53.5400	22.8939
3	3.2772	3.8533	3.6239	4.1359	9.9807	22.4876	57.3790	116.5676	75.8448	27.4145
4	2.9767	4.3920	--	4.7185	10.2752	22.6223	59.2268	112.5722	58.8581	27.9258
5	3.1058	3.8850	3.4814	4.0745	9.6127	20.2513	51.6940	82.8139	52.7315	24.6798
6	3.0177	3.9548	3.1600	3.8463	11.4523	19.1631	45.1399	81.4676	41.7008	21.1760
Mean	3.2670	4.0643	3.3386	3.9826	9.6411	20.1965	52.2018	92.8746	53.6565	23.5824
Std Dev	0.5099628	0.300078	0.249643	0.449899	1.234798	1.973586	5.234801	17.144693	13.19347	3.979641

Table B-7. Baseline CO2 g/m										
Run/Notch	LoIdle	HiIdle	1	2	3	4	5	6	7	8
1	589.91	700.77	2837.84	5063.71	8686.95	10634.24	14191.49	20911.82	21818.06	23628.23
2	624.58	722.77	2968.35	4857.69	8304.13	10889.92	14062.89	18559.33	21323.99	22482.71
3	740.32	838.43	3270.43	5207.93	8217.08	11434.16	14024.48	21005.17	23179.52	22803.38
4	647.96	764.45	3054.82	5078.92	9355.64	11246.40	14786.20	21525.32	22248.56	22519.25
5	721.56	828.59	3488.05	4897.19	9148.02	11253.84	14099.30	22046.87	23539.76	22257.26
6	430.98	690.63	3100.02	5057.62	9051.08	11677.90	14528.50	20673.11	22092.45	21039.57
Mean	625.88	757.61	3119.92	5027.17	8793.82	11189.41	14282.14	20786.94	22367.06	22455.07
Std Dev	111.372	64.105	230.368	129.021	467.147	375.189	306.881	1197.586	838.351	842.054

Table B-8. Treated CO2 g/m										
Run/Notch	LoIdle	HiIdle	1	2	3	4	5	6	7	8
1	665.64	719.25	2703.02	4337.98	7602.14	10283.03	13722.95	18169.20	20904.99	20776.47
2	700.86	807.19	3015.80	4734.76	7735.14	10092.16	13363.56	18116.75	22680.87	22202.88
3	675.99	716.69	2711.22	4556.08	7944.08	10746.60	14304.83	20075.83	22908.92	23292.69
4	722.48	756.53	--	4644.63	7953.80	10590.92	14648.39	20467.60	23806.95	23634.06
5	755.90	817.20	2954.74	4738.98	8118.21	10559.64	14151.28	19779.93	23198.02	22455.21
6	728.31	786.78	3094.46	5017.46	8222.91	9899.31	13248.05	18636.06	21419.53	22390.62
Mean	708.20	767.27	2895.85	4671.65	7929.38	10361.94	13906.51	19207.56	22486.55	22458.66
Std Dev	34.018	43.466	179.287	225.177	231.277	326.349	553.355	1026.048	1105.048	997.698

Table B-9. Baseline NOx g/m										
Run/Notch	LoIdle	HiIdle	1	2	3	4	5	6	7	8
1	14.165	13.625	53.652	93.655	137.097	176.822	215.371	379.667	395.722	458.255
2	16.568	19.040	59.342	90.811	143.971	179.990	219.196	340.091	394.655	446.234
3	18.370	19.864	66.538	102.611	142.838	181.156	222.406	375.733	466.166	454.432
4	17.112	20.004	64.244	97.897	160.618	190.084	237.298	414.008	426.255	514.568
5	18.707	19.809	70.694	96.804	157.498	185.876	222.753	373.248	486.428	450.324
6	16.799	19.881	66.919	104.227	159.057	195.031	236.452	391.229	462.435	445.007
Mean	16.953	18.704	63.565	97.668	150.180	184.827	225.579	378.996	438.610	461.470
Std Dev	1.6160	2.5121	6.1235	5.1259	10.0493	6.8386	9.1494	24.2206	38.8267	26.4827

Table B-10. Treated NOx g/m										
Run/Notch	LoIdle	HiIdle	1	2	3	4	5	6	7	8
1	15.262	15.625	54.108	90.139	132.127	168.476	222.850	367.297	444.469	429.372
2	15.583	17.070	59.814	91.974	135.388	169.013	224.555	352.938	459.500	437.856
3	15.817	17.118	54.460	89.105	139.988	178.664	233.974	369.272	444.145	450.800
4	17.204	17.997	--	94.349	131.202	177.832	243.482	389.670	477.454	461.138
5	17.190	18.074	57.616	91.510	130.413	176.999	233.204	393.657	470.761	447.914
6	16.409	17.312	62.647	115.154	149.787	190.364	225.746	388.712	465.269	468.620
Mean	16.244	17.199	62.576	95.372	136.484	176.891	230.635	376.924	460.266	449.284
Std Dev	0.8280	0.8848	3.6176	9.8538	7.4051	7.9805	7.8009	16.1740	13.7157	14.4614

Table B-11. Baseline THC g/m										
Run/Notch	LoIdle	HiIdle	1	2	3	4	5	6	7	8
1	1.2062	1.5255	1.5489	2.2743	3.4425	4.4934	5.1786	9.3959	10.7570	11.0834
2	1.4721	1.6567	1.5481	3.3546	3.0660	4.1375	5.0873	8.6909	10.4446	10.7893
3	1.5520	1.9256	1.8339	2.5044	3.2651	4.5536	5.5659	9.7531	11.7961	11.3099
4	1.5156	1.8395	1.6666	2.4962	7.5950	4.6910	5.5371	9.8553	10.9244	10.5140
5	1.0045	1.5704	1.6203	1.5487	2.9783	3.7965	4.8631	8.8179	10.9227	10.6174
6	0.8870	1.3099	1.4146	1.8445	2.8440	4.0305	4.9261	8.5805	10.1843	9.0942
Mean	1.2729	1.6379	1.6054	2.3371	3.8651	4.2838	5.1930	9.1823	10.8382	10.5680
Std Dev	0.283501	0.222954	0.140776	0.625572	1.839476	0.348011	0.299661	0.558704	0.551578	0.780065

Table B-12. Treated THC g/m										
Run/Notch	LoIdle	HiIdle	1	2	3	4	5	6	7	8
1	1.5523	1.7537	1.1909	1.9441	2.1984	3.6081	4.8961	7.5692	7.8794	7.2715
2	1.1962	1.4218	1.1395	1.7648	2.3754	3.6795	4.9269	7.6627	10.1692	9.6396
3	0.9160	1.2533	1.0892	1.5603	2.2673	3.4340	4.9373	8.4216	9.7386	9.9794
4	1.0807	1.3962	--	1.8203	2.3170	3.2890	5.3224	8.5260	9.8726	8.6835
5	1.0355	1.1564	1.2075	1.5540	2.3357	3.2874	4.7254	7.5571	9.5527	8.7907
6	0.6626	0.8423	0.9249	1.1770	1.9647	2.4415	3.7850	6.4722	7.4780	7.4071
Mean	1.0739	1.3040	1.1104	1.6367	2.2431	3.2899	4.7655	7.7015	9.1151	8.6286
Std Dev	0.296453	0.304003	0.113574	0.271536	0.14942	0.445811	0.518782	0.741513	1.137721	1.114432

Table B-13. Baseline TPM g/m										
Run/Notch	LoIdle	HiIdle	1	2	3	4	5	6	7	8
1	0.22354	0.29247	0.81087	1.45507	3.67758	5.06325	6.87389	7.91973	8.90640	9.20165
2	0.20090	0.30205	0.86890	1.47894	3.77941	5.71156	7.40327	10.74562	9.90038	10.97464
3	0.16834		0.57652	0.94248	2.86055	4.23285	5.82316	6.81528	8.07628	8.07667
4	0.17574	0.27061	0.84171	1.32253	3.67139	5.43872	7.14004	9.84217	9.09528	7.81088
5	0.33802	0.30339	0.77358	1.22327	3.71691	5.22991	6.94766	8.81205	8.33556	8.70294
6	0.11788	0.12798	--	--	4.19927	4.22765	5.55494	8.03041	6.66067	7.40686
Mean	0.20407	0.25930	0.77431	1.28446	3.65085	4.98399	6.62383	8.69421	8.49576	8.69561
Std Dev	0.074617	0.074572	0.11613	0.217413	0.435285	0.62276	0.751662	1.422028	1.101835	1.28661

Table B-14. Treated TPM, g/m										
Run/Notch	LoIdle	HiIdle	1	2	3	4	5	6	7	8
1	0.2382	0.2896	1.5535	2.1041	4.7730	6.3857	8.3957	13.9702	18.3239	18.6820
2	0.2424	0.3689	1.0970	--	--	7.3891	10.6331	15.0642	21.8134	20.6544
3	0.2955	0.2616	0.8340	1.6803	5.0635	7.2658	10.1478	14.4036	19.4659	20.6783
4	0.5564	0.4551	1.3450	2.4339	5.5492	8.0061	11.0248	18.9022	23.4480	23.7695
5	0.1135	0.3214	1.0306	2.1552	5.8125	7.7994	11.2015	17.4596	25.0533	26.3077
6	0.2728	0.1510	0.9840	2.5031	6.3120	8.2087	11.5060	18.2054	25.8815	27.0281
Mean	0.2865	0.3080	1.1407	2.1753	5.5020	7.5091	10.4848	16.3342	22.3310	22.8533
Std Dev	0.1464942	0.102664	0.262583	0.325892	0.607955	0.656709	1.126778	2.1114216	3.0265	3.381343

Table B-15. Peak Opacity						
Baseline				Treated		
Notch	Mean	Std Dev		Notch	Mean	Std Dev
Lo Idle	4.01	4.46		Lo Idle	4.42	2.43
Hi Idle	3.99	2.34		Hi Idle	3.81	1.83
1	9.86	2.75		1	8.84	1.35
2	14.46	3.11		2	11.87	1.73
3	18.76	3.42		3	13.59	1.11
4	25.34	4.24		4	15.45	1.56
5	28.98	5.98		5	15.98	2.14
6	28.98	6.14		6	17.88	1.96
7	19.98	6.89		7	11.04	2.67
8	10.78	3.97		8	7.52	1.46

Table B-16. 30-Second Peak Opacity						
Baseline				Treated		
Notch	Mean	Std Dev		Notch	Mean	Std Dev
Lo Idle	3.48	4.40		Lo Idle	4.18	2.33
Hi Idle	3.04	2.48		Hi Idle	2.58	2.17
1	7.99	2.26		1	7.20	1.34
2	8.76	2.30		2	7.54	0.91
3	15.55	3.00		3	11.68	1.14
4	21.91	3.88		4	13.52	1.50
5	25.48	5.16		5	14.15	2.03
6	25.73	5.38		6	13.47	1.00
7	14.62	4.36		7	8.39	1.63
8	5.65	3.48		8	3.86	1.38

Table B-17. Steady-State Opacity						
Baseline				Treated		
Notch	Mean	Std Dev		Notch	Mean	Std Dev
Lo Idle	3.78	4.57		Lo Idle	4.31	2.40
Hi Idle	3.75	2.32		Hi Idle	2.75	2.67
1	7.11	2.31		1	6.05	1.77
2	8.32	2.43		2	7.16	0.96
3	14.66	2.79		3	11.02	1.09
4	21.38	3.50		4	13.52	1.53
5	24.61	5.07		5	14.22	2.34
6	22.22	5.16		6	10.48	2.11
7	11.10	2.72		7	5.88	0.84
8	4.39	3.46		8	3.53	1.77

Table B-18. Baseline RPM										
Run / Notch	LoIdle	Idle	1	2	3	4	5	6	7	8
1				384	492	565	653	729	828	910
2	254	321	304	383	489	569	651	730	825	910
3	254	320	302	383	491	569	651	732	830	914
4	253	320	303	383	492	566	651	737	829	911
5	254	319	297	382	495	567	650	731	829	
6	253	319	296	386	493	569	651	731	829	913
Averages	254	320	300	384	492	568	651	732	828	912
Std Dev	0.49	0.75	3.26	1.26	1.83	1.61	0.90	2.56	1.60	1.62

Table B-19. Treated RPM

Run / Notch	LoIdle	Idle	1	2	3	4	5	6	7	8
1	254	320	319	389	499	573	656	733	830	913
2	254	318	318	388	498	574	655	733	830	913
3	253	318	317	388	498	574	656	732	--	915
4	253	319	316	387	499	573	652	733	830	914
5	253	317	316	387	498	573	653	733	831	915
6	254	320	316	387	496	573	655	732	830	916
Averages	254	319	317	388	498	573	655	733	830	914
Std Dev	0.55	1.21	1.26	0.82	1.10	0.52	1.64	0.52	0.45	1.21

Table B-20. Baseline Main Generator Voltage, V

Run / Notch	LoIdle	Idle	1	2	3	4	5	6	7	8
1	2.9	3.7	263.3	343.2	454.1	525.2	606.0	754.1	797.6	840.3
2	3.4	3.9	259.2	342.3	452.0	520.2	607.5	681.4	794.3	841.0
3	3.1	3.9	262.3	343.2	452.3	524.1	604.8	739.6	803.4	840.7
4	3.4	3.9	258.7	341.4	451.5	522.2	603.9	743.4	796.4	840.5
5	3.2	3.9	260.4	343.0	451.0	521.4	603.2	677.1	796.4	839.3
6	2.7	3.7	257.4	339.8	450.0	520.1	605.5	679.7	796.4	839.7
		Averages	260.2	342.2	451.8	522.2	605.2	712.6	797.4	840.3
		Std Dev	2.2	1.3	1.4	2.1	1.6	36.7	3.1	0.7

Table B-21. Baseline Main Generator Current, A

Run / Notch	LoIdle	Idle	1	2	3	4	5	6	7	8
1	6.0	8.5	804.0	1046.1	1375.7	1583.6	1818.8	2235.9	2358.4	2467.4
2	8.5	11.0	792.1	1041.6	1366.8	1566.4	1819.7	2030.2	2339.6	2468.9
3	6.9	9.6	801.3	1045.2	1367.3	1574.7	1811.6	2192.7	2367.3	2467.0
4	8.5	11.0	791.0	1040.3	1366.8	1573.2	1811.0	2205.7	2349.8	2469.7
5	7.2	9.7	796.0	1045.3	1365.4	1571.0	1807.1	2024.7	2339.3	2447.4
6	7.2	9.7	786.4	1034.5	1360.9	1566.4	1814.3	2025.1	2346.5	2464.1
		Averages	795.1	1042.2	1367.1	1572.5	1813.7	2119.0	2350.2	2464.1
		Std Dev	6.6	4.4	4.8	6.4	4.8	102.2	11.0	8.4

Table B-22. Treated Main Generator Voltage, V										
Run / Notch	LoIdle	Idle	1	2	3	4	5	6	7	8
1	1.9	2.7	266.5	351.0	463.8	539.5	625.8	753.1	833.1	835.4
2	2.4	3.4	266.9	350.5	464.5	539.1	623.8	748.4	833.4	836.4
3	2.6	3.4	259.0	348.8	461.0	536.8	622.7	741.4	822.6	837.8
4	2.7	3.5	265.2	349.9	462.4	537.5	624.8	743.1	835.0	836.4
5	2.7	3.7	261.0	349.2	462.2	538.5	626.5	747.4	834.4	836.3
6	2.4	3.4	270.4	367.6	476.5	546.7	633.9	756.5	831.7	834.7
		Averages	264.8	352.8	465.1	539.7	626.2	748.3	831.7	836.1
		Std Dev	4.2	7.3	5.7	3.6	4.0	5.7	4.6	1.1

Table B-23. Treated Main Generator Current, A										
Run / Notch	LoIdle	Idle	1	2	3	4	5	6	7	8
1	2.8	5.1	817.8	1074.4	1409.5	1633.3	1885.4	2241.7	2463.6	2469.0
2	4.6	7.2	819.3	1073.1	1412.3	1630.5	1875.6	2224.8	2460.0	2466.1
3	5.0	7.2	792.4	1065.0	1398.2	1621.0	1870.4	2205.0	2430.4	2466.2
4	3.7	6.0	809.4	1064.5	1398.4	1620.5	1873.4	2206.4	2456.2	2462.4
5	5.0	7.2	796.1	1062.6	1398.1	1622.2	1877.5	2222.0	2457.1	2461.0
6	4.2	6.1	826.8	1120.7	1446.4	1651.9	1899.3	2251.9	2460.0	2467.8
		Averages	810.3	1076.7	1410.5	1629.9	1880.2	2225.3	2454.6	2465.4
		Std Dev	13.6	22.1	18.7	12.0	10.6	18.7	12.1	3.1

Table B-24. Baseline Fan Hp								
Run / Notch	1	2	3	4	5	6	7	8
1	0.0	11.2	16.0	21.5	51.6	66.5	95.4	113.4
2	8.9	11.2	16.2	39.3	27.7	68.5	95.4	110.9
3	0.0	11.2	16.2	21.3	51.8	67.2	81.1	112.9
4	0.0	11.0	15.9	20.6	52.5	66.3	94.3	110.6
5	0.0	11.0	15.8	20.9	51.7	62.8	119.4	112.7
6	8.3	11.1	16.4	38.9	27.2	68.8	96.5	111.9
Averages	2.9	11.1	16.1	27.1	43.8	66.7	97.0	112.1
Std Dev	4.4	0.1	0.2	9.3	12.6	2.2	12.4	1.1

Table B-25. Treated Fan Hp								
Run / notch	1	2	3	4	5	6	7	8
1	0.0	16.4	21.4	25.3	53.3	32.3	79.5	87.0
2	0.0	16.7	21.8	25.1	53.8	68.4	75.1	82.8
3	0.0	16.1	20.9	24.7	29.0	32.0	85.0	84.2
4	1.3	17.9	22.8	26.4	29.0	34.8	76.4	88.5
5	0.0	16.1	21.1	24.9	28.8	62.4	75.3	89.3
6	0.0	16.9	21.3	24.7	28.8	31.2	78.7	87.8
Averages	0.2	16.7	21.5	25.2	37.1	43.5	78.3	86.6
Std Dev	0.5	0.7	0.7	0.7	12.7	17.1	3.7	2.6

Table B-26. Baseline Exhaust Temperatures, °C										
Run / Notch	LoIdle	Idle	1	2	3	4	5	6	7	8
1	103	94	150	194	253	299	355	384	382	384
2	106	94	148	198	260	311	351	393	328	383
3	104	92	145	196	253	302	355	390	383	385
4	105	94	148	196	246	305	355	388	381	378
5	102	92	145	211	258	306	354	391	383	383
6	114	95	146	191	114	309	351	387	377	378
		Averages	147	198	231	305	354	389	372	382
		Std Dev	1.8	6.8	57.2	4.5	2.1	3.3	21.7	3.2

Table B-27. Treated Exhaust Temperatures, °C										
Run / Notch	LoIdle	Idle	1	2	3	4	5	6	7	8
1	84	84	139	196	253	297	347	458	458	458
2	113	74	102	147	209	256	311	326	331	336
3	134	78	103	143	206	256	306	331	334	337
4	128	79	103	151	213	262	313	333	339	338
5	121	78	105	147	210	260	308	328	332	334
6	111	75	106	158	214	264	304	320	326	328
		Averages	110	157	218	266	315	349	353	355
		Std Dev	14.2	19.7	17.8	15.6	16.2	53.2	51.3	50.4

Table B-28. Baseline Intake Air Temperatures, °C										
Run / Notch	LoIdle	Idle	1	2	3	4	5	6	7	8
1	19.7	20.5	22.2	23.3	24.1	24.8	24.9	25.2	26.4	27.4
2	29.6	28.7	28.8	28.5	27.2	26.5	26.9	26.4	25.8	25.4
3	21.5	21.8	22.1	22.9	24.2	25.3	25.0	25.1	25.3	26.8
4	26.1	26.0	26.1	24.6	24.6	25.4	24.6	24.1	24.0	23.6
5	25.6	25.5	25.8	25.5	25.8	27.2	25.3	25.0	25.0	24.7
6	24.9	24.4	24.0	23.7	24.2	23.2	22.5	22.4	22.1	22.0
		Averages	24.8	24.8	25.0	25.4	24.9	24.7	24.8	25.0
		Std Dev	2.57	2.07	1.26	1.39	1.41	1.34	1.55	2.02

Table B-29. Treated Intake Air Temperatures, °C										
Run / Notch	LoIdle	Idle	1	2	3	4	5	6	7	8
1	9.2	8.8	8.8	8.9	9.7	9.7	10.6	12.7	17.2	16.8
2	6.6	6.4	7.0	7.4	9.7	10.0	10.0	11.7	14.0	14.5
3	14.1	14.3	13.9	14.0	15.5	15.8	17.9	18.3	18.2	18.1
4	10.8	11.1	11.2	12.0	12.5	13.3	16.3	17.5	19.0	16.4
5	14.2	12.5	12.7	12.0	12.3	11.9	13.0	15.3	14.6	14.0
6	2.2	2.2	4.1	4.4	5.8	7.0	8.2	9.8	10.3	12.3
		Averages	9.6	9.8	10.9	11.3	12.7	14.2	15.6	15.4
		Std Dev	3.68	3.54	3.31	3.07	3.80	3.39	3.25	2.13

Table B-30. Baseline Ambient Pressure, (mmHg)										
Run / Notch	LoIdle	Idle	1	2	3	4	5	6	7	8
1	757.7	757.5	756.8	755.0	752.4	748.8	747.3	747.2	747.2	746.3
2	746.4	746.4	746.4	746.3	746.0	745.9	746.6	747.0	744.8	741.6
3	754.9	754.8	754.4	753.6	751.6	749.7	749.6	749.0	749.0	748.3
4	747.2	747.0	747.0	747.2	747.2	746.5	746.1	746.1	746.8	746.6
5	748.1	747.5	747.5	747.1	747.0	747.0	747.3	747.8	747.9	747.8
6	747.9	748.2	748.5	749.1	749.3	749.6	750.1	750.8	751.3	751.5
		Averages	750.1	749.7	748.9	747.9	747.8	748.0	747.8	747.0
		Std Dev	4.37	3.70	2.64	1.65	1.62	1.69	2.19	3.24

Table B-31. Treated Ambient Pressure, (mmHg)										
Run / Notch	LoIdle	Idle	1	2	3	4	5	6	7	8
1	749.2	748.8	749.6	749.6	750.3	750.1	750.5	750.7	750.1	750.3
2	757.6	757.1	756.3	755.3	754.0	753.0	752.6	752.8	752.6	751.9
3	748.6	748.6	748.8	749.9	751.5	751.7	751.7	751.7	750.9	750.7
4	757.3	756.3	755.3	754.6	754.4	754.8	755.3	755.7	755.1	755.5
5	756.1	755.5	755.7	755.5	755.1	754.9	754.9	754.6	754.4	754.4
6	764.6	764.6	764.0	763.8	763.0	762.8	763.0	762.8	762.1	761.7
		Averages	755.0	754.8	754.7	754.6	754.7	754.7	754.2	754.1
		Std Dev	5.49	5.15	4.45	4.44	4.48	4.36	4.32	4.26