FINAL DETAILED REPORT

LOCOMOTIVE FIELD DEMONSTRATION OF TIER 4 PM EMISSION CONTROL

Funded by
California Air Resources Board
Air Quality Improvement Program
and
Bay Area Air Quality Management District
Grant No. G10-AQIP-12

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EXECUTIVE SUMMARY

This report documents the results of a locomotive diesel particulate filter (DPF) retrofit project, funded in part by California AB118 AQIP and sponsored by Bay Area Air Quality Management District (BAAQMD). The project participants include BAAQMD, California Air Resources Board (CARB), BNSF Railway, and GT Exhaust, which is the grant recipient and DPF manufacturer.

The locomotive used for this project was BNSF1284, a 2,100 horsepower NREC model 3GS21B, originally manufactured in April, 2008. This switcher locomotive uses three diesel-engine driven generator sets (Gen Set 1, 2, and 3) to provide the power needed to drive the traction motors. The GT DPF retrofit system uses catalyzed DPF elements with passive regeneration capability. Initial testing (see SwRI interim report for projects 03.17106 and 03.17160) showed that the DPFs reduced the PM emissions to 0.012 g/hp-hr or 61 percent below the locomotive Tier 4 limits. This phase of the project was to demonstrate the performance of the DPFs while BNSF1284 was in revenue service for 1,500 hours (approximately 6 months).

After DPF installation and baseline testing at SwRI, BNSF1284 returned to revenue service in Richmond, California. SwRI's on-board data acquisition system was used to monitor the locomotive to record engine speeds, fuel rates, exhaust temperatures, and exhaust pressures. It was observed that the locomotive was operated as a remote control system which results in excessive starts and stops of the three engines. It was noted that this is not acceptable operating conditions for the DPF. Towards the end of March 2012 after approximately 350 hours of RCL operation, the Gen 3 DPF housing failed due to high pressure.

After the initial DPF housing failure, the locomotive was sent from Richmond to Barstow, California for removal of the DPF, and the DPF was sent to GT for inspection and repair. The locomotive returned to revenue service in Richmond in May 2012, during which time the locomotive was in operation for a short period of time with the datalogger not functioning. Once the datalogger was reconnected, it was noted that the back pressure was extremely high, and GT requested transfer of the locomotive to SwRI for DPF inspection and reprogramming the RCl to prevent the frequent starts and stops of the engine.

BNSF1284 was returned to SwRI for repair of the DPF systems and for reprogramming the RCL to reduce the excessive engine starts and stops in June 2012. While there, SwRI had to troubleshoot some engine performance issues unrelated to the DPF. Therefore, the locomotive did not return to revenue service until October 2012. At this point, the locomotive had approximately 1000 hours of DPF equipped operation.

The reprogramming of the RCL did not reduce the transient nature of the engines, although it did reduce the number of times they were started and stopped. While observing the operation, it was noted that the back pressure remained at acceptable levels. However, GT was forced to end the project prematurely when a manufacturing facility closure in the DPF supply chain meant there would no longer be a commercially available product. The 1500 hour mid-point test became the final test and was completed in February 2013, after 1990 hours of operation.

The final test in February 2013 showed that PM was reduced to 0.027 g/hp-hr or 10% below Tier 4 PM requirements limits. The DPFs were removed and returned to GT for inspection and the original mufflers were reinstalled on the locomotive. BNSF 1284 returned to revenue service in Richmond, CA.

ACKNOWLEDGEMENTS

This project would like to acknowledge the support of BNSF Railway Company (BNSF). BNSF provided the test locomotive for this demonstration project and for the transportation between Richmond, California and San Antonio, Texas.

Funding for a portion of this project was provided by BAAQMD funding under the California Air Resources Board's Air Quality Improvement Program (AQIP) Grant Number G10-AQIP-12.

NOTES

At the beginning of this project and throughout the majority of this project, the technology demonstrator was known as GT Exhaust. In September of 2012, GT Exhaust was purchased by IAC Acoustics and now goes by the name IAC Acoustics. For simplicity, the technology demonstrator is referred to as GT Exhaust, or GT, throughout this document.

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1.0 Introduction and Background

The Air Quality Improvement Program (AQIP), established by the California Alternative and Renewable Fuel, Vehicle Technology, Clean Air, and Carbon Reduction Act of 2007 (California Assembly Bill 118 (AB 118), Statutes of 2007, Chapter 750) is a voluntary incentive program administered by the California Resources Board (CARB) to fund clean vehicle and equipment projects, research on biofuels production and the air quality impacts of alternative fuels, and workforce training. Within the AQIP are Advanced Technology Demonstration Projects, with the purpose of helping accelerate the next generation of advanced technology vehicles, equipment, or emission controls which are not yet commercialized.

As part of a CARB funded AB 118 project, sponsored by BAAQMD, GT Exhaust's passive Diesel Particulate Filter (DPF) system was field demonstrated for almost 2000 hours on a NRE 3GS-21B genset switcher locomotive, BNSF1284. Southwest Research Institute (SwRI) performed all of the testing and data collection mentioned in this report. SwRI Report 03-17106, "Exhaust Emissions Testing Support of Locomotive DPF Field Demonstration", prepared by Steven G. Fritz and John C. Hedrick in February 2012, summarizes:

- 1.1 the test methodology utilized in all emissions tests
- 1.2 the baseline data
- 1.3 the initial installation of the DPF
- 1.4 the initial test results of BNSF1284 after this installation

This initial report from SwRI is attached as Appendix A in this report.

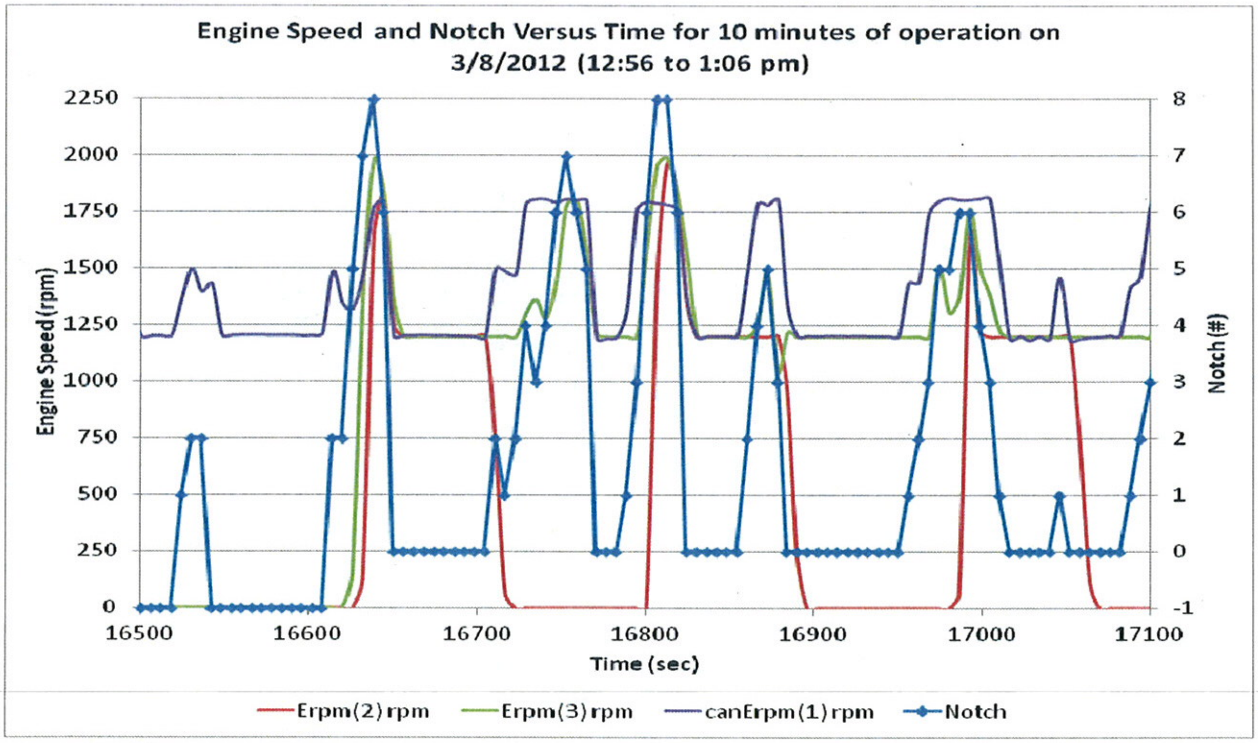
This Final Report summarizes the occurrences during the initial phase of BNSF1284 revenue operation and the final test data.

2.0 Phase 1 of the Field Demonstration

BNSF1284 started its revenue service in Richmond, California in February 2012. This locomotive is a remote control locomotive (RCL). Figure 2.1 below is a capture of a 10 minute interval of the BNSF1284 operation under RCL control with Erpm(2), Erpm(3) and canErpm(1) being the data labels used to describe the measured engine speeds in rpm from engines 2, 3, and 1, respectively. As seen in the graph, the locomotive throttle notch command increases and decreases rapidly causing excessive engine starts followed by essentially no load on the just-started engines causing them to shut down and overall lower exhaust temperatures. These three items are not acceptable operating conditions for a passive Diesel Particulate Filter.

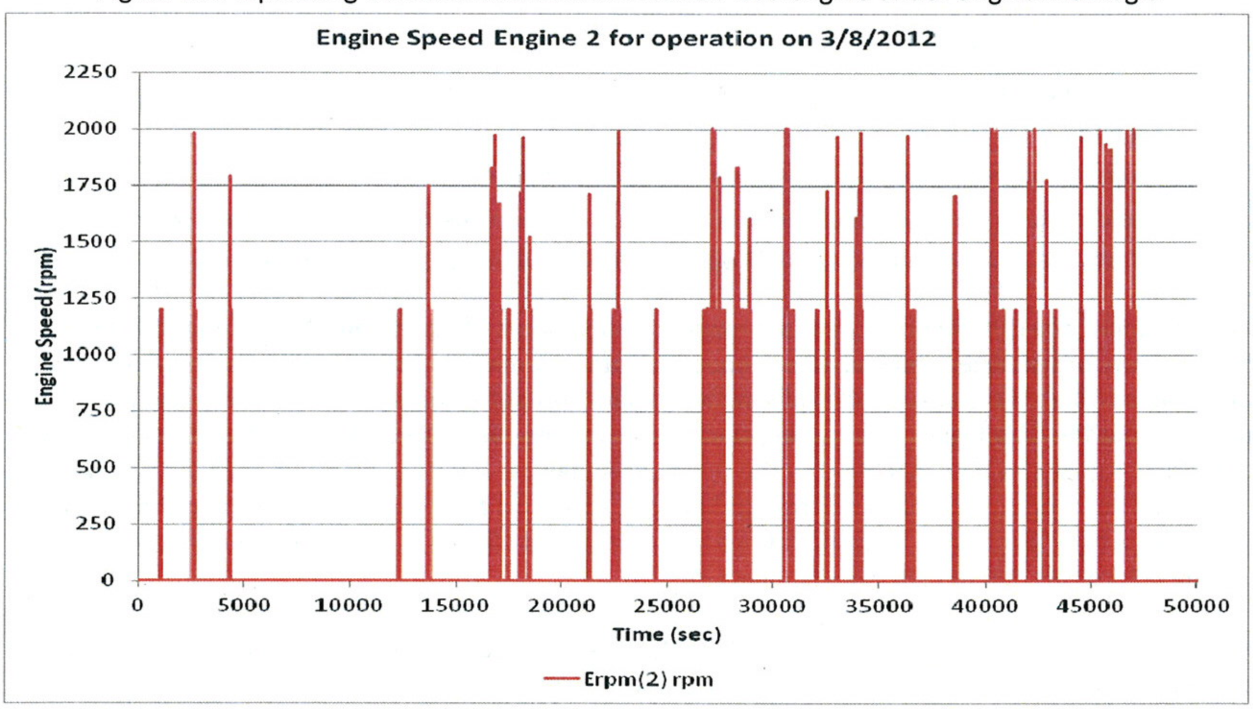
On this day, 3/8/2012, Engine 1 was the lead engine. The two charts shown in Figure 2.2 and Figure 2.3 monitor the behavior of Engine 2 and Engine 3, respectively, on this same day. During the operation on this day, Engine 2 had 44 stop / starts and Engine 3 had 30 stop / starts, with essentially no significant engine load for any useful duration during any of these starts.

Figure 2.1: Operating Characteristics of the locomotive under original RCL Logic



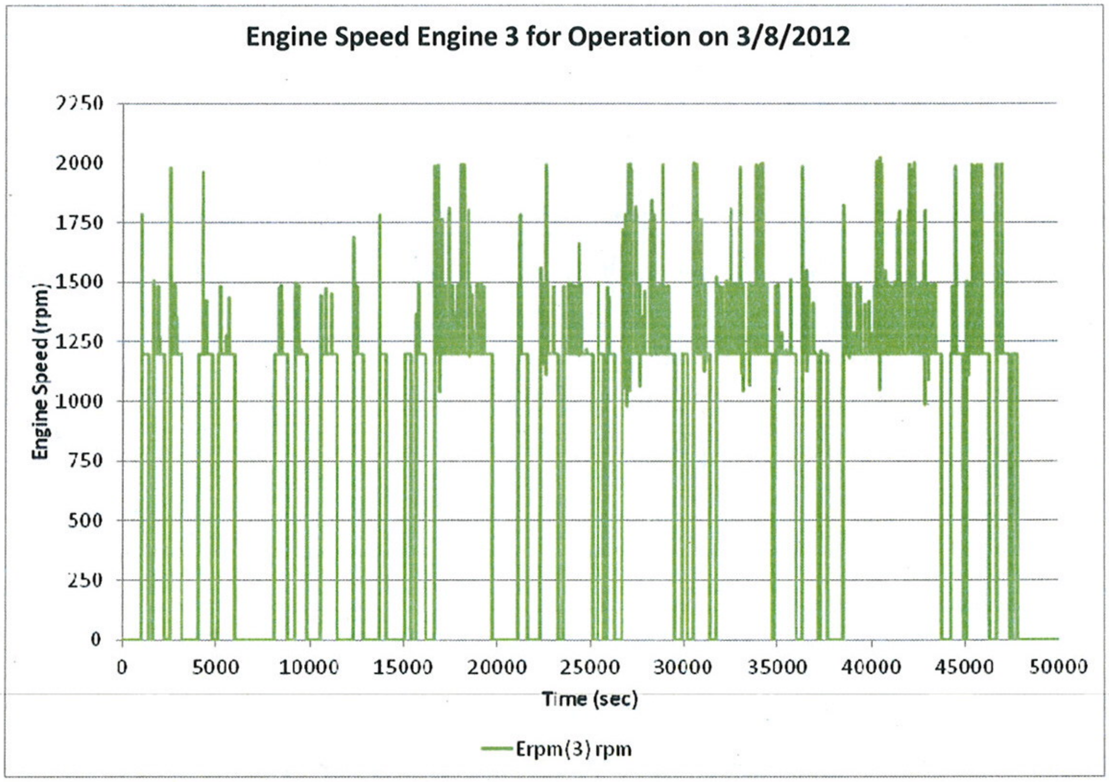
Note: Erpm(2) and Erpm(3) are engine speed in rpm of engines 2 and 3, respectively. canErpm(1)rpm is the CAN based engine rpm (speed) for GEN1 (generator set 1). CAN (controller area network) is the SAE J1939 communication standard for heavy-duty vehicles and non-road engines.

Figure 2.2: Operating characteristics of the first non-lead engine under original RCL logic



Note: Erpm(2) is the engine speed in rpm of engine 2.

Figure 2.3: Operating conditions of the second non-lead engine under original RCL logic



Note: Erpm(3) is the engine speed in rpm of engine 3.

This RCL operation caused problems for the DPF, as summarized below.

- High soot loading occurs during startup.
- Notch command increase and decrease duration periods are short, typically less than 60 seconds.
- Multiple notch changes occur over a short period of time.
- Rapid notch command could result in a start-up of an engine that isn't necessary, which also affects the primary engine as it will operate under lower loads and lower exhaust temperatures.

The first failure of a DPF occurred after approximately 350 hours of operation. At the time of failure, there were inconsistencies and questions about the data that made it difficult to determine if the data was reliable. There were also periods of time when data was not recorded because there was a suspicion that the data logger was causing electrical problems. Because of the frequent starts and stops of the locomotive, it was suspected that the DPF housing failure was due to an extremely high back pressure. The locomotive was transferred to Barstow, California for removal of the DPF so that it could be sent back to GT Exhaust in Lincoln, Nebraska, for repair. In Lincoln, it was confirmed that the DPF housing failure was due to high exhaust pressure.

Once the locomotive was back in service and the data issues were resolved, it was noted that the exhaust pressures were dangerously high. As a result, GT requested that the locomotive be taken out of service and transferred to SwRI for reprogramming the RCL and inspecting / repairing the DPF system.

The new remote control logic would prevent an engine from shutting down until it had been idling for 5 consecutive minutes, ideally preventing an engine from shutting down just to be restarted immediately again. The locomotive remained at SwRI from June 2012 to November 2012 because of the RCL reprogramming and DPF system repair, as well as various locomotive issues that had to be troubleshot and repaired. During this time, the locomotive ran for about 650 hours, increasing the total DPF-equipped locomotive hours to 1000.

The locomotive returned to revenue service in November 2012 in Fort Worth, Texas to save the transfer time between SwRI and Richmond, CA. The change in the RCL improved the operating characteristics significantly from before. Comparing to the 14 hour day discussed above where the non-lead engines started and stopped 44 and 36 times, on a 11 hour day on 12/6/2012, the non-lead engines started and stopped only 16 and 4 times. However, the load on the non-lead engines was still only needed for less than one minute at a time. This would mean that an engine would idle for 5 minutes every time a higher load was needed for a few seconds.

The two charts below show examples of times when all three engines were operating. The chart in Figure 2.4 shows a 20 minute period and Figure 2.5 shows a different 10 minute period on the same day. In both cases, Engine 3 was the lead engine and when the Engine 1 and Engine 2 were started, they were only needed for short periods of times. As a result, they spend most of the time at idle. During the whole day Engine 1 was on for only 25 minutes, but 22 of those minutes were at idle conditions (or 88% of the time) and Engine 2 was on for 126 minutes, but 116 of those minutes were at idle (or 92% of the time).

Figure 2.4: 20 minute operating period of the locomotive after the reprogramming of the RCL

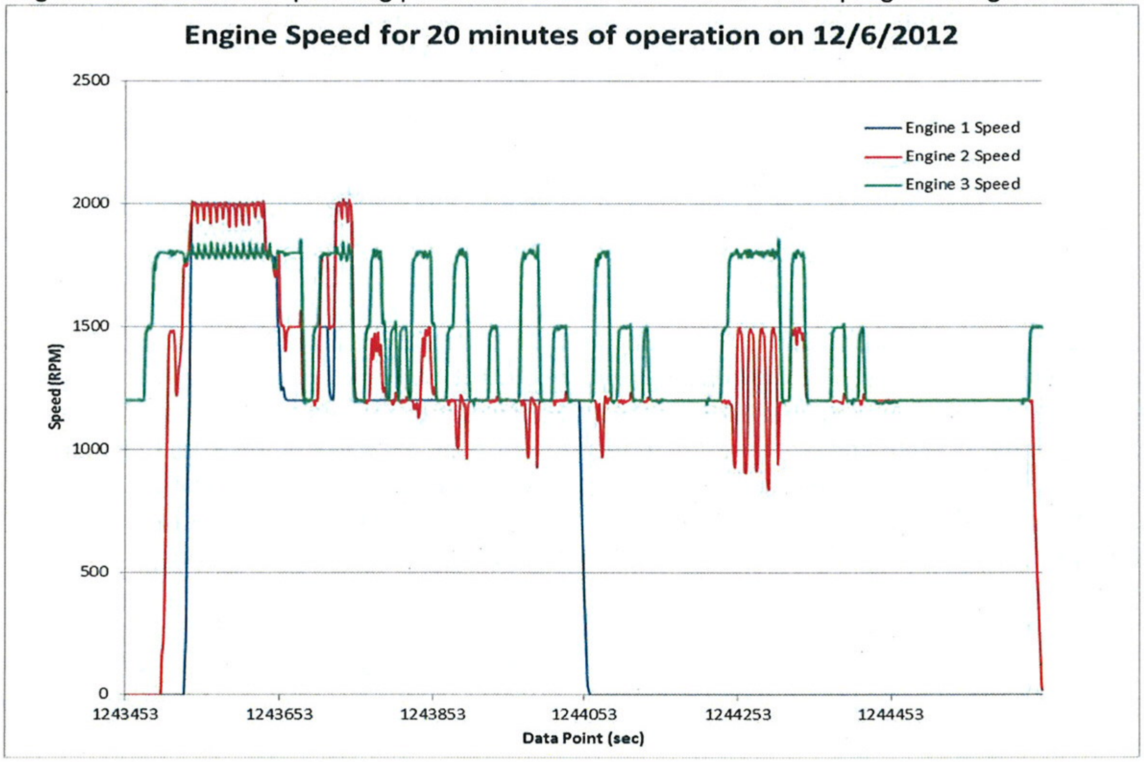
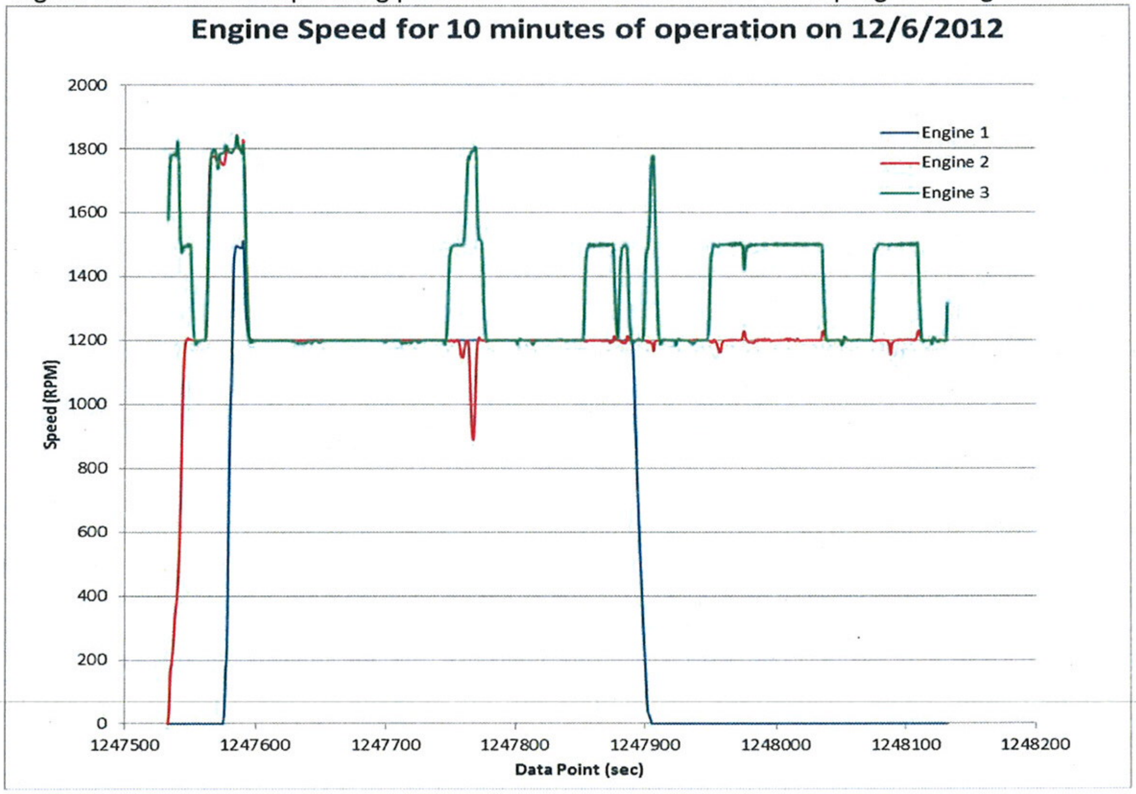


Figure 2.5: 10 minute operating period of the locomotive after the reprogramming of the RCL



Although the reprogrammed RCL significantly reduced the frequency of the stops and starts of the non-lead engine, it is still not ideal operating conditions for a passive DPF system for the following reasons:

- Exhaust temperatures at idle are only around 400°F which is not hot enough for the passive regeneration to occur.
- Passive DPFs typically require 15 to 20 minutes at or above the regeneration temperature in order to burn off the soot and prevent the back pressure from getting too high.

In December 2012, GT Exhaust learned of the closure of the plant that manufacturers the DPF substrate that was being demonstrated. For this reason, there would no longer be a commercially viable product at the end of the project and any new DPF substrate supplier would necessitate a "do over" of the full verification program. CARB and GT therefore agreed to complete the mid-point test as the final test and to proceed with the final report without completing the second part of the demonstration. After 1990 hours of operation, the locomotive was returned to SwRI for its final emissions test. Chart 2.1 below shows the percentage of time spent in each notch for the first 1224 hours of operation.

Chart 2.1: Percentage of time BNSF1284 spent in each operation Notch

	Idle Hours	N1 Hours	N2 Hours	N3 Hours	N4 Hours	N5 Hours	N6 Hours	N7 Hours	N8 Hours
Hours	1566	238	210	163	28	15	6	2	15
% Total	69.81%	10.61%	9.36%	7.28%	1.25%	0.67%	0.26%	0.10%	0.66%

3.0 Testing Protocol and Background

Testing with the GT Exhaust's DPF installed on BNSF1284 was conducted with a single batch of commercially available Texas Low Emission Diesel - Ultra Low Sulfur Diesel fuel (TxLED – ULSD). Properties for the TxLED - ULSD fuel is provided in Table 3.1.

Table 3.1. – TxLED-ULSD Fuel Properties

ASTM Method	Test Property	Units	BNSF1284 ULSD
D240	Heat of Combustion		
	Gross	BTU / lb	19,736
	Net	BTU / lb	18,510
D4052	API Gravity	--	37.4
	Specific Gravity	--	0.8378
	Density at 15°C	grams / L	837.4
D5186	Total Aromatics	mass %	23.9
	Mono Aromatics	mass %	20.6
	Polynuclear Aromatics	mass %	3.2
D5291	Elemental Analysis		
	Carbon Content	weight %	86.42
	Hydrogen Content	weight %	13.44
D5453	Sulfur Content	ppm	9.6

SwRI performed exhaust emission tests in all phases of the project using the Federal Test Procedure (FTP) for locomotives, as detailed in Title 40 of the U. S. Code of Federal Regulations (CFR), Part 92, Subpart B. In accordance with the FTP, emissions of HC, CO, NO_X, and PM were measured for each throttle notch. This data was used to calculate the US EPA Switch Cycle weighted composite emission level for each pollutant. Smoke opacity by FTP was also measured as part of the testing. More details of the measurement techniques can be found in Section 2.5 of Appendix A, Milestone 1 Report.

No engine-out baseline emission measurements were made on BNSF1284. To provide a basis of comparison, baseline engine-out emissions data on Union Pacific Railroad switcher locomotive, UPY2737, was used to compare results from BNSF1284 with the DPF installed. The UPY2737 is a NREC locomotive Model 3GS21B. part The baseline engine-out emissions test on the UPY2737 were conducted under a previous CARB project (CARB Agreement No. 08-409), The UPY2737 baseline consisted of triplicate FTP's that used TxLED-ULSD diesel fuel and a single FTP test that used high-sulfur (2,814 ppm) EPA locomotive certification fuel.

The baseline EPA Switcher-Cycle exhaust emissions for UPY2737 are summarized in Table 3.2. On TxLED-ULSD fuel, baseline engine-out FTP emission levels from UPY2737 were in-line with expected values based on Cummins Tier 3 non-road engine certification test data, with average Switcher-Cycle NO_X of 3.0 g/hp-hr and PM of 0.11 g/hp-hr. The coefficient of variance (c.o.v.) is also included for reference.

Table 3.2: UPY2737 Baseline Test with EPA Switch Cycle Results

Date	Fuel	Test	EPA Switch Cycle				
			obs bsfc	HC	CO	NOx	PM
			lb/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr
22-Jan-10	TxLED-ULSD	FTP-1	0.412	0.13	1.26	2.9	0.11
25-Jan-10	TxLED-ULSD	FTP-2	0.414	0.12	1.21	3.0	0.10
25-Jan-10	TxLED-ULSD	FTP-3	0.426	0.13	1.26	3.0	0.11
Avg. TxLED-ULSD			**0.417**	**0.13**	**1.24**	**3.0**	**0.11**
ULSD c.o.v.			2%	5%	2%	1%	4%
26-Jan-10	2814 ppmS Cert	FTP-4	0.424	0.13	1.36	3.1	0.16
ULSD avg vs. HSD			**0.006**	**(0.00)**	**0.12**	**0.10**	**0.06**
ULSD avg vs. HSD, % diff			2%	-1%	10%	3%	53%

The UPY2737 baseline FTP using high-sulfur (HSD) EPA certification diesel fuel (2814 ppmS) was conducted to check the emissions sensitivity of the GenSet Switcher to high sulfur fuel. The changes in emissions, also show in Table 3.2, were within the range expected, with NO_X increasing slightly and PM increasing significantly, a 53 percent increase from 0.11 g/hp-hr to 0.16 g/hp-hr, due to the high sulfur content of the fuel.

4.0 Final Test

The same exhaust collector or manifold that was used for the baseline tests on UPY2737 and the initial test on the BNSF1284 with the DPFs installed was used to test the BNSF 1284 after 1990 hours of operation. As with the baseline tests, this exhaust collector handled the total locomotive exhaust flow as a "System" rather than attempting to sample from each exhaust stack individually (see Figure 3.1 below). The NREC 3GS21B locomotive on the BNSF railroad are not equipped with dynamic brakes with an integral self load feature, so an external load bank was used to load the engines.

Figure 4.1: Exhaust collection manifold on BNSF1284 during final test

For comparison purposes, the initial test results (0 hours of operation) of BNSF1284 with the installed DPFs are shown below in Table 4.11. The test results from BNSF1284 after 1990 hours of operation are shown in Table 4.2 below and the full data set is provided in Appendix B. Only one FTP test was performed for the final test, so the coefficient of variability (c.o.v.) is inapplicable and therefore not included in the table.

Table 4.1: BNSF1284 EPA Switch Cycle Results with GT DPF Installed, 0 hours of operation

			EPA Switch Cycle				
			obs bsfc	HC	CO	NOx	PM
Date	Fuel	Test	lb/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr
23-Jan-12	TxLED-ULSD	FTP-2	0.424	0.04	0.009	2.9	0.011
24-Jan-12	TxLED-ULSD	FTP-3	0.428	0.04	0.006	2.9	0.013
25-Jan-12	TxLED-ULSD	FTP-4	0.423	0.04	0.005	2.8	0.011
GT Exhaust (FTP 2->4) AVG			**0.425**	**0.04**	**0.007**	**2.9**	**0.012**
GT DPF c.o.v.			1%	7%	33%	2%	9%
UP2737 Baseline avg vs. GT DPF, % diff			–	-70%	-99%	-4%	-89%
Percent of EPA Tier 4 Levels			–	-73%	--	119%	-61%

Table 4.2: BNSF EPA Switch Cycle Results with GT DPF Installed, 1990 hours of operation

			EPA Switch Cycle				
			obs bsfc	HC	CO	NOx	PM
Date	Fuel	Test	lb/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr
4-Feb-13	TxLED-ULSD	FTP-5	0.407	0.021	0.032	3.00	0.027
UP2737 Baseline Avg vs GT DPF 1990h, % diff			-	-84%	-98%	0%	-75%
GT DPF New vs GT DPF 1990h, % diff			-	-47%	353%	3%	127%
GT DPF Percent of EPA Tier 4 Levels			-	-85%	-	131%	-9%

The DPF did meet the requirements for reducing the particulate matter to levels below the EPA Tier 4 limits of 0.03 g/hp-hr, although there was more particulate matter bypassing the filters after 1990 hours of operation than when new. The increase in particulate bypass was caused by small deformations in the holsters where the filters are inserted. These deformations may have been caused by the excessive pressures during the early phases of the demonstration project, but can be reduced with small design modifications to increase the durability in these areas.

5.0 Conclusions

The conclusions below are based on the experiences with the GT Exhaust passive DPF system installed on a multi-engine switcher locomotive operated as an RCL. During this demonstration period, the locomotive was never operated in normal service without RCL, so we cannot conclude how the passive DPF system would work under those circumstances.

- In this specific application with RCL, the 2nd and 3rd engines are called upon infrequently and only for short periods of power. The rest of the time, they are operated at idle or off, neither condition having enough temperature to allow the soot to be regenerated in the DPF. Because of this, soot will likely build up in the DPF causing the back pressure to increase to levels above the engine manufacturer's specifications. As a result, there will need to be a method of adding heat to the exhaust into the DPF to activate regeneration at idle conditions. This could be accomplished by adding a heat source to each locomotive individually as part of the DPF package; or by providing a single load bank at the railyard for regenerating the filters as part of a maintenance schedule, ideally no more frequently than the existing maintenance schedules.

- Even with an external heat source, if a site plans to operate a multi-engine switcher as an RCL with DPFs, it will be necessary to validate that the RCL logic does not turn on and off the non-lead engines excessively. If it does, the logic should be modified.
- The GT Exhaust housing for the DPFS was designed to be compact and replace the existing mufflers with very minimal modifications to the locomotive. The housings fit completely under the roof of the locomotive. From the test results and final inspection, it is concluded that the basic design concept, with small improvements, will be able to maintain the PM below Tier 4 levels.

Appendix A- Milestone 1

Exhaust Emissions Testing Support of Locomotive DPF Field Demonstration

INTERIM REPORT

SwRI Project No. 03.17106 and 03.17160

Prepared For

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Results and discussion given in this report relate only to the test items described in this report.

EXECUTIVE SUMMARY

This report documents the initial test results of a locomotive diesel particulate filter (DPF) retrofit project, funded in part by California AB118 AQIP and sponsored by Bay Area Air Quality Management District (BAAQMD). The project participants include BAAQMD, California Air Resources Board (CARB), BNSF Railway, and GT Exhaust, which is the grant recipient and DPF manufacturer.

The locomotive used for this project was BNSF1284, a 2,100 horsepower NREC model 3GS21B, originally manufactured in April, 2008. This switcher locomotive uses three diesel-engine driven generator sets (Gen Set 1, 2, and 3) to provide the power needed to drive the traction motors. The locomotive was moved from BNSF Railroad's Richmond California fleet to SwRI Locomotive Technology Center (LTC) in San Antonio, Texas for installation and testing of GT Exhaust Diesel Particulate Filter (DPF) retrofit system.

The GT Exhaust DPF retrofit system uses catalyzed DPF elements. The catalyzed coating on the DPF offered a significant HC, CO, and PM emissions reduction. Additionally, this catalyzed coating should allow the diesel particulate filters to passively regenerate at moderate exhaust temperatures, thus keeping the engine back pressure within allowable limits.

The GT Exhaust DPF housings were installed in place of the standard mufflers on each of the three engines. The GT Exhaust DPF housing is roughly the same size as the stock muffler. The only locomotive modification needed to install the GT Exhaust DPF housing was to the muffler mounting platform, directly above the engine, where the exhaust pipe opening needed to be enlarged. There are no external modifications to the locomotive car body needed to install the GT Exhaust DPF.

After installation of the DPF's, they were degreened by operating the engines at rated power for 20 hours. After degreening, the locomotive was emissions tested followed Title 40 of the U. S. Code of Federal Regulations (CFR), Part 92, Subpart B. The addition of the DPF reduced the PM emissions to 0.012 g/hp-hr or 61 percent below the locomotive Tier 4 PM limits.

BNSF1284 was returned to revenue service in Richmond, California in February 2012 with the GT Exhaust DPF retrofit system installed on all three engines. Additional emissions tests are planned at 1,500 hours (6 months) and 3,000 hours (12 months) of revenue service operation.

ACKNOWLEDGMENTS

This project would like to acknowledge the support of BNSF Railroad. BNSF Railroad provided the test locomotive for this demonstration project and for the transportation between Richmond, California and San Antonio, Texas.

Funding for a portion of this project was provided by BAAQMD Air Quality Improvement Program (AQIP) Grant Number G10-AQIP-12.

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1.0 INTRODUCTION AND BACKGROUND

The Air Quality Improvement Program (AQIP), established by the California Alternative and Renewable Fuel, Vehicle Technology, Clean Air, and Carbon Reduction Act of 2007 (California Assembly Bill (AB) 118, Statutes of 2007, Chapter 750), is a voluntary incentive program administered by the California Air Resources Board (CARB) to fund clean vehicle and equipment projects, research on biofuels production and the air quality impacts of alternative fuels, and workforce training. Within the AQIP are Advanced Technology Demonstration Projects, with the purpose of helping accelerate the next generation of advanced technology vehicles, equipment, or emission controls which are not yet commercialized.

As part of a California AB118 project, sponsored by BAAQMD, GT Exhaust's Diesel Particulate Filter (DPF) will be field demonstrated for 3,000 hours on a NRE 3GS-21B genset switcher locomotive, BNSF1284. This Interim Report covers the initial installation of the DPF and initial test results. Additional exhaust emissions tests are planned after 1,500 hours (6 months) and 3,000 hours (12 months) of revenue service operation in Richmond, California.

2.0 TECHNICAL APPROACH

Exhaust emissions testing on BNSF1284 and GT Exhaust DPF's installation was performed by Southwest Research Institute (SwRI) at the SwRI Locomotive Technology Center (SwRI LTC) in San Antonio, Texas. The technical approach used to conduct the exhaust emission testing is presented below. Included is a brief description of the test locomotive, engine power measurements, fuel consumption measurements, exhaust emissions test procedures, and particulate measurement equipment and procedures.

2.1 Test Locomotive

Locomotive BNSF1284 was used for this project and was provided by BNSF Railroad. BNSF1284 was manufactured by NREC in April 2008, and is a Model 3GS21B Ultra-Low Emissions Locomotive (ULEL). This locomotive is powered by three engine driven generator sets, each using a 19-liter Cummins QSK19C diesel engine. The Cummins QSK19 engines are in-line six cylinder configuration, turbocharged, and air-to-air aftercooled. Each of the three engines is capable of developing 700 horsepower (522 kW) for a total locomotive power output of 2,100 horsepower (1,566 kW).

BNSF1284 is one of the 72 of this type of locomotives the BNSF operates in California and Texas. These locomotives are certified as EPA Tier 2 locomotive emissions levels and are typically operate in urban areas due to the low emissions of these switcher locomotives. BNSF1284 is shown in Figure 1, and general locomotive information is shown in Table 1

Figure 1. Test Locomotive BNSF1284

TABLE 1. GENERAL LOCOMOTIVE DATA

Model designation	3GS21B
Locomotive Power (gross)	2100 HP
Engine Model	QSK19C
Generator Model	572RDL
Weight - Fully Serviced	268,000lbs
Wheel Arrangement (AAR)	B-B
BNSF1284's Emissions Sticker	
	

2.2 Power Measurements

The electric power produced by the three gen sets, normally sent to the traction motors in the locomotive, was rerouted to an external electrical resistance grid. The gross power of all three engines was determined by using three 3-phase watt meters, one per each of the three gen sets in the locomotive, and the manufacturer's published alternator efficiencies to calculate the engine gross or flywheel power. The locomotive's auxiliary power consumption was included as part of the generator power output measurements.

2.3 Fuel Consumption Measurements

Diesel fuel consumption was measured on a mass flow basis using a Micro Motion® mass flow meter. The fuel measurement system was equipped with a heat exchanger to control engine fuel supply temperature. Hot fuel, normally returned to the locomotive fuel tank, was cooled before returning to the fuel measurement reservoir ("make-up tank") to assure a consistent fuel supply temperature at the engine.

2.4 Test Fuel

Testing with the GT Exhaust's DPF installed on BNSF1284 was conducted with a single batch of commercially available TxLED – ULSD diesel fuel. Properties for the TxLED - ULSD fuel is provided in Table 2.

TABLE 2. TXLED - ULSD FUEL PROPERTIES

ASTM Method	Test Property	Units	BNSF1284 ULSD
D240	Heat of Combustion		
	Gross	BTU / lb	19,736
	Net	BTU / lb	18,510
D4052	API Gravity	--	37.4
	Specific Gravity	--	0.8378
	Density at 15°C	grams / L	837.4
D5186	Total Aromatics	mass %	23.9
	Mono Aromatics	mass %	20.6
	Polynuclear Aromatics	mass %	3.2
D5291	Elemental Analysis		
	Carbon Content	weight %	86.42
	Hydrogen Content	weight %	13.44
D5453	Sulfur Content	ppm	9.6

2.5 Exhaust Emissions Test Procedure

SwRI performed exhaust emission tests using the Federal Test Procedure (FTP) for locomotives, as detailed in Title 40 of the U. S. Code of Federal Regulations (CFR), Part 92, Subpart B. In accordance with the FTP, emissions of HC, CO, NO_X, and PM were measured for each throttle notch. This data was used to calculate the US EPA Switch Cycle weighted composite emission level for each pollutant. Smoke opacity by FTP was also measured as part of the testing.

2.5.1 Gaseous Emissions Sampling

The three exhaust stacks were routed into a common exhaust stack extension or manifold that was mounted above the roof of the locomotive, as shown on a similar locomotive in Figure 2. The combination of the exhaust from all three engines allowed for a single gaseous sample probe to be mounted in a section of pipe near the outlet of the manifold. This permitted the emissions sampling system to meet the requirements found in Title 40 of the U. S. CFR, Part 92, Subpart B.

Figure 2. Example of Exhaust Sampling Manifold

A heated sample line was used to transfer the raw exhaust sample from the probe mounted in the exhaust manifold to the emission instruments used to measure the raw exhaust concentrations of hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and oxides of nitrogen (NO_X) at each operating mode.

Hydrocarbon concentrations were determined using a California Analytical Instruments Model 300 heated flame ionization detector (HFID), calibrated on propane. NO_X concentrations were measured using a California Analytical Instruments Model 400 heated chemiluminescent detector (HCLD). NO_X correction factors for engine intake air humidity were applied as specified by EPA in 40 CFR §1065.670. Concentrations of CO and CO_2 were determined by non-dispersive infrared (NDIR) instruments and O_2 concentrations were measured using a magneto-pneumatic analyzer.

Gaseous mass emission rates were computed using the measured concentrations, the observed (measured) fuel consumption rate, and calculated engine airflow. Engine airflow was not directly measured in this test program. Instead, engine airflow was determined using the carbon balance following the FTP method, relying on knowledge of the concentrations of the carbon-containing constituents in the exhaust (CO_2, CO, and HC), along with the fuel carbon content, to compute the fuel/air ratio (f/a). Engine airflow rate was then computed using the measured fuel consumption rate and the computed f/a ratio. The sum of measured fuel and computed intake air was taken as the mass flow of exhaust.

2.5.2 Particulate Emissions Sampling

Particulate (PM) emissions were measured at each test mode using a "split then dilute" technique, in which a portion of the raw exhaust was "split" from the total flow and mixed with filtered air in an 8-inch diameter dilution tunnel. The raw split sample was transferred from a particulate sample probe, mounted in the common exhaust manifold shown in Figure 2, to the dilution tunnel via a short insulated pipe between the exhaust stack extension and the entry of the particulate dilution tunnel.

After adequate dilution, a particulate sample was extracted from the dilution tunnel using a sample probe to transfer sample to the filter holder. Particulate was accumulated on two 90 mm fluorocarbon-coated glass fiber filters (Pallflex T60A20) in series at a target filter face velocity of 70 cm/s for 1,800 seconds. The sample filters were mounted in a stainless steel filter holder connected to the sample probe. Particulate filters were preconditioned and weighed before and after testing, following the FTP. The particulate mass emission rate was computed using the mass collected on the filters, the volume of dilute exhaust drawn through the filters, and dilution air and raw exhaust flow parameters.

Note that the typical PM sampling time in a Part 92 locomotive test is 350 seconds. However, due to the extremely low PM levels downstream of the DPF, the sampling times were increased to 1800 seconds in an attempt to obtain reasonable mass loading on the PM sample filters.

Due to the low levels of PM emissions emitted with the DPF installed, the particulate sampling system components were cleaned and conditioned before testing BNSF1284 with the DPF's installed. Additional PM sample filters (Tunnel Blanks) were taken after the completion of each FTP test to quantify the PM levels that are an artifact in the dilution tunnel and sampling system. With the engine off, "tunnel blank" sampling was started with the no adjustment to the dilution tunnel flow, with sampling for the same duration as the during the FTP test (1,800 seconds). PM results were then calculated without a tunnel blank correction, but a Tunnel Blank correction to the PM measurement is available.

3.0 TEST RESULTS

The test results of the project are given in the following sections:

- Baseline FTP data from UPY2737
- GT exhaust DPF installation and test results from BNSF1284

3.1 Baseline FTP Data from UPY2737

No engine-out baseline emission measurements were made on BNSF1284. To provide a basis of comparison, baseline engine-out emissions data on UPY2737 (Shown in Figure 2), as part of a previous CARB project,[1] was used to compare results from BNSF1284 with the DPF installed. The UPY2737 baseline consisted of triplicate FTP's that used TxLED-ULSD diesel fuel and a single FTP test that used high-sulfur (2,814 ppm) EPA locomotive certification fuel.

The baseline EPA Switcher-Cycle exhaust emissions for UPY2737 are summarized in Table 3 and detailed notch-by-notch results for each test are included in Appendix A. On TxLED-ULSD fuel, baseline engine-out FTP emission levels from UPY2737 were in-line with expected values based on Cummins Tier 3 non-road engine certification test data, with average Switcher-Cycle NO_X of 3.0 g/hp-hr and PM of 0.11 g/hp-hr.

TABLE 3. UPY2737 BASELINE TEST EPA SWITCH CYCLE RESULTS

Date	Fuel	Test	EPA Switch Cycle				
			obs bsfc	HC	CO	NOx	PM
			lb/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr
22-Jan-10	TxLED-ULSD	FTP-1	0.412	0.13	1.26	2.9	0.11
25-Jan-10	TxLED-ULSD	FTP-2	0.414	0.12	1.21	3.0	0.10
25-Jan-10	TxLED-ULSD	FTP-3	0.426	0.13	1.26	3.0	0.11
Avg. TxLED-ULSD			**0.417**	**0.13**	**1.24**	**3.0**	**0.11**
ULSD c.o.v.			2%	5%	2%	1%	4%
26-Jan-10	2814 ppmS Cert	FTP-4	0.424	0.13	1.36	3.1	0.16
ULSD avg vs. HSD			**0.006**	**(0.00)**	**0.12**	**0.10**	**0.06**
ULSD avg vs. HSD, % diff			2%	-1%	10%	3%	53%

The UPY2737 baseline FTP using high-sulfur (2814 ppm S) EPA certification diesel fuel was conducted to check the emissions sensitivity of the GenSet Switcher to high sulfur fuel. The changes in emissions, also show in Table 3, were within the range expected, with NO_X increasing slightly and PM increasing significantly, a 53 percent increase from 0.11 g/hp-hr to 0.16 g/hp-hr, due to the high sulfur content of the fuel.

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[1] SwRI Final Report 03.15322, "NREC GenSet Locomotive DPF Assessment" by J.C. Hedrick and S.G. Fritz, Final Report to CARB under CARB Agreement 08-409, November, 2010.

3.2 BNSF1284 GT Exhaust DPF Installation on BNSF1284 and Test Results

The GT Exhaust DPF housing was designed to directly replace the NREC locomotive muffler / silencer, which is shown in Figure 3. No modifications to the roof of the locomotive long hood were required to accommodate the installation of the GT Exhaust DPF (Figure 4). The only modification required to the locomotive was to the deck under the muffler / silencer (directly over the engine). The DPF housing had a larger diameter exhaust pipe connecting the turbocharger to the inlet of the DPF housing. This larger diameter exhaust pipe required a larger opening in the deck. Figure 5 shows BNSF1284 with the GT Exhaust DPF's installed.

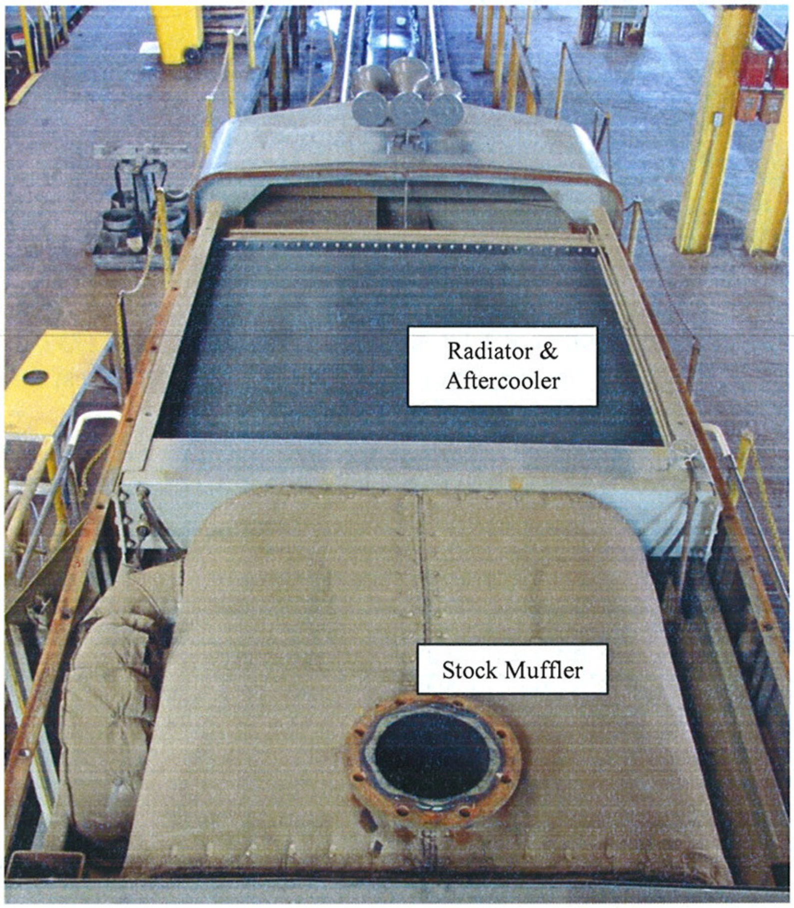

Figure 3. Stock Muffler Visible After Removal of Roof Section

Figure 4. GT Exhaust DPF Installed

Figure 5. BNSF1284 With GT Exhaust DPF's Installed

The same exhaust collector or manifold that was fabricated for the baseline tests on UPY2737 was used to test BNSF1284 with the GT Exhaust DPF's installed. As with the baseline tests, this exhaust collector handled the total locomotive exhaust flow as a "system," rather than attempting to sample from each exhaust stack individually (See Figure 2). NREC 3GS21B locomotives on the BNSF Railroad are not equipped with dynamic brakes with an integral self load feature, so an external load bank was used to load the engines.

After the DPF installation process was completed, the DPF systems were degreened by operating each of the three Genset engines for 20 hours at rated power. This degreening process allowed the diesel particulate filters to be conditioned before exhaust emissions testing was started. Additionally this operating time was used to assure that there were no exhaust leaks or thermal issues caused by the installation of the DPF's.

Triplicate FTP tests were performed on BNSF1284 with the DPF's installed. The test results with the GT Exhaust DPF' installed are shown in Table 4 and the full data set is provided in Appendix B. Compared to the UPY2737 engine-out baseline test results, the GT Exhaust DPF's reduced the HC emissions by 70 percent and essentially eliminated CO emissions (99% reduction). A slight decrease (four percent reduction) in NO_X emission is probably not significant between the two locomotives. The PM emissions from BNSF1284 were 89% lower than the baseline, engine-out, PM emissions measured on UPY2737. The BNSF1284 PM emissions were 61 percent below the US EPA Tier 4 locomotive PM limit of 0.03 g/hp-hr, which goes into effect for new locomotives starting 2015.

Smoke opacity measurements were taken during the triplicate emission tests and the results were below five percent opacity for all conditions. The low smoke opacity level was expected due to the very low PM emissions with the DPF's installed.

TABLE 4. BNSF1284 EPA SWITCH CYCLE RESULTS WITH GT EXHAUST DPF INSTALLED

			EPA Switch Cycle				
			obs bsfc	HC	CO	NOx	PM
Date	Fuel	Test	lb/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr
23-Jan-12	TxLED-ULSD	FTP-2	0.424	0.04	0.009	2.9	0.011
24-Jan-12	TxLED-ULSD	FTP-3	0.428	0.04	0.006	2.9	0.013
25-Jan-12	TxLED-ULSD	FTP-4	0.423	0.04	0.005	2.8	0.011
GT Exhaust (FTP 2->4) AVG			**0.425**	**0.04**	**0.007**	**2.9**	**0.012**
GT DPF c.o.v.			1%	7%	33%	2%	9%
UP2737 Baseline avg vs. GT DPF, % diff			–	-70%	-99%	-4%	-89%
Percent of EPA Tier 4 Levels			–	-73%	--	119%	-61%

Upon the departure of BNSF1284 from SwRI's LTC, the hours of engine operation with the DPF's installed were:

Gen 1 = 57.6 hours
Gen 2 = 36.6 hours
Gen 3 = 42.8 hours

These hours include the 20 hours of operation to degreening the DPF's, engine operation during the triplicate emissions tests, and other debugging operation on the locomotive.

4.0 CONCLUSIONS

The GT Exhaust Diesel Particulate Filter systems installed on BNSF1284 offered significant reductions in FTP Switch cycle HC, CO, and PM emissions when compared to the baseline locomotive, UPY2737. The EPA Switch Cycle PM emissions from BNSF1284 with the DPF's installed were 89 percent lower that the baseline PM emissions measured on UPY2737, and were 61 percent below the US EPA Tier 4 PM limit of 0.03 g/hp-hr.

Appendix B – Final Test Data

Locomotive BNSF1284 : GT Exhaust DPF at 1,500 hours
Tested 4-FEB-2013 @ SwRI

Notch	Gross HP	obs Fuel Rate (lb/hr)	obs bsfc (lb/hp-hr)	HC (g/hr)	CO (g/hr)	Corr. NOx (g/hr)	Obs. PM (g/hr)	CO2 (g/hr)	
Idle	18	14.9	0.834	4	1	152	0.64	21,512	
1	217	87.6	0.403	5	8	592	4.47	126,394	
2	363	142.4	0.392	2	10	864	28.04	205,593	
3	648	237.5	0.366	5	11	1,792	8.37	342,796	
4	644	252.9	0.393	13	56	1,745	8.75	365,017	GEN 2 Hunting
5	725	274.5	0.379	5	11	2,182	7.20	396,286	GEN 2 Hunting
6	1,320	499.2	0.378	9	32	3,804	9.27	720,572	GEN 2 &3 Hunting
7	1,778	668.3	0.376	9	19	4,645	9.14	964,727	
8	1,961	738.0	0.376	10	20	5,287	8.55	1,065,458	

Notes:

LI = Idle = DB2

Not dynamic brake equipped

EPA Switcher Duty Cycle Weighted Results

Notch	WF	w-BHP	obs w-Fuel w-(lb/hr)	w-HC w-(g/hr)	w-CO w-(g/hr)	w-NOx w-(g/hr)	Obs. w-PM w-(g/hr)	w-CO2 w-(g/hr)
Idle	59.8%	10.7	8.9	2.4	0.7	91.0	0.38	12,864
1	12.4%	26.9	10.9	0.6	1.0	73.4	0.55	15,673
2	12.3%	44.6	17.5	0.3	1.2	106.2	3.45	25,288
3	5.8%	37.6	13.8	0.3	0.6	103.9	0.49	19,882
4	3.6%	23.2	9.1	0.5	2.0	62.8	0.31	13,141
5	3.6%	26.1	9.9	0.2	0.4	78.5	0.26	14,266
6	1.5%	19.8	7.5	0.1	0.5	57.1	0.14	10,809
7	0.2%	3.6	1.3	0.0	0.0	9.3	0.02	1,929
8	0.8%	15.7	5.9	0.1	0.2	42.3	0.07	8,524
sum =	100.0%	208.2	84.8	4.4	6.6	624.6	5.67	122,376
			0.407	**0.02**	**0.03**	**3.00**	**0.027**	**588**
			obs bsfc	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)

Modal Brake-Specific Emissions

Notch	HC (g/hp-hr)	CO (g/hp-hr)	Corr. NOx (g/hp-hr)	Obs. PM (g/hp-hr)	Tunnel BG Corr PM (g/hp-hr)	CO2 (g/hp-hr)
Idle	0.22	0.06	8.52	0.036	0.000	1,204
1	0.02	0.04	2.73	0.021	0.000	582
2	0.01	0.03	2.38	0.077	0.000	567
3	0.01	0.02	2.76	0.013	0.000	529
4	0.02	0.09	2.71	0.014	0.000	567
5	0.01	0.02	3.01	0.010	0.000	547
6	0.01	0.02	2.88	0.007	0.000	546
7	0.01	0.01	2.61	0.005	0.000	542
8	0.01	0.01	2.70	0.004	0.000	543

EPA Freight Duty Cycle Weighted Results

Notch	WF	w-BHP	obs w-Fuel w-(lb/hr)	w-HC w-(g/hr)	w-CO w-(g/hr)	w-NOx w-(g/hr)	Obs. w-PM w-(g/hr)	w-CO2 w-(g/hr)
Idle	50.5%	9.0	7.5	2.0	0.6	76.9	0.32	10,863
1	6.5%	14.1	5.7	0.3	0.5	38.5	0.29	8,216
2	6.5%	23.6	9.3	0.2	0.6	56.1	1.82	13,364
3	5.2%	33.7	12.3	0.3	0.6	93.2	0.44	17,825
4	4.4%	28.3	11.1	0.6	2.5	76.8	0.38	16,061
5	3.8%	27.5	10.4	0.2	0.4	82.9	0.27	15,059
6	3.9%	51.5	19.5	0.3	1.3	148.3	0.36	28,102
7	3.0%	53.3	20.0	0.3	0.6	139.3	0.27	28,942
8	16.2%	317.6	119.6	1.6	3.3	856.6	1.39	172,604
sum =	100.0%	558.8	215.5	5.7	10.3	1568.6	5.55	311,036
			0.386	**0.01**	**0.02**	**2.81**	**0.010**	**557**
			obs bsfc	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)

Fuel-Specific Emissions

Notch	HC (g/lb fuel)	CO (g/lb fuel)	Corr. NOx (g/lb fuel)	Obs. PM (g/lb fuel)	Tunnel BG Corr PM (g/lb fuel)	CO2 (g/lb fuel)
Idle	0.27	0.08	10.21	0.043	0.000	1,443
1	0.06	0.09	6.76	0.051	0.000	1,443
2	0.02	0.07	6.06	0.197	0.000	1,444
3	0.02	0.05	7.55	0.035	0.000	1,444
4	0.05	0.22	6.90	0.035	0.000	1,443
5	0.02	0.04	7.95	0.026	0.000	1,444
6	0.02	0.06	7.62	0.019	0.000	1,444
7	0.01	0.03	6.95	0.014	0.000	1,444
8	0.01	0.03	7.16	0.012	0.000	1,444