AIR QUALITY IMPROVEMENT PROGRAM (AQIP)
(Pursuant to AB 118)
ADVANCED TECHNOLOGY DEMONSTRATION PROJECT

Final Report of Tier IV Particulate Matter Retrofit System on UPY-2755 (Genset Switch Locomotive)

December 2, 2013

Grant No.: G09-AQIP-13

Prepared for:
Gary Lee Moore
Interim Executive Director
City of Los Angeles Harbor Department
425 South Palos Verdes Street
San Pedro, CA 90731

Prepared by:
Jose G. Ramirez
Sr. Project Engineer, Johnson Matthey SEC LLC

Table of Contents

Acronyms and Abbreviations 5

ACKNOWLEDGMENTS 6

EXECUTIVE SUMMARY 7

INTRODUCTION AND BACKGROUND 7
PROJECT BUDGET 8
PROJECT TIMELINE 8
PROJECT MILESTONES 11

AFTER-TREATMENT INSTALLATION 13
Description of Locomotive CCRT (L-CCRT) 14

3000-Hour EVALUATION RESULTS 16

3000 HOUR DURABILITY PERIOD AND PERFORMANCE 21

CONCLUSIONS 24

REFERENCES 26

APPENDIX A: SWRI 3000-hour Test Report 27

sub-APPENDIX A: Baseline Engine Out Emissions Data from UPY2737 51

APPENDIX B: Zero Hour Emissions Data from UPY2755 with
the JM L-CCRT DPF Installed 56

APPENDIX C: 1,500 Hour Emissions Data from UPY2755 with
the JM L-CCRT DPF Installed 60

APPENDIX D: 3,000 Hour Emissions Data from UPY2755 with
the JM L-CCRT DPF Installed 64

APPENDIX E: 3,000 Hour PM Sample Filter Analysis for SOF and Sulfate.....69

APPENDIX F: Photos of UPY-2755 equipped with three JM L-CCRT™ 72

APPENDIX G: SWRI-LTC Repair Report for Engine#3, 2012 81

APPENDIX H: 2600 Hour Repair Report for Engine#3, 1/16/2013 104

List of Tables

Table 1: Project Budget 8
Table 2: Test sequence for locomotives and locomotive engines 16
Table 3: FTP Results for Baseline, 0-hour, 1500 Hour and 3000 Hour Tests 18
Table 4: NREC Rated Power at each Notch Setting 21
Table 5: Estimated Performance of UPY-2755 during the 3000 hour durability operation 22
Table 6: Notch-3 EGP FTP Results 24
Table 7: Malfunction Schedule for UPY-2755 during the 3000-Hour Durability Period 106

List of Figures

Figure: 1 Union Pacific UPY-2755 schematic of 3 GS-21B ULEL Switch Locomotive .. 8
Figure 2: Project Timeline 9
Figure 3: Durability Hour Accumulation for 3000 Hour Durability Period..... 10
Figure 4: Union Pacific Switch Locomotive UPY-2755 fully equipped with 3 L-CCRT's 13
Figure 5: Union Pacific Switch Locomotive UPY-2755 in original state..... 14
Figure 6: L-CCRT Installed on one Genset of UPY-2755, with Engine Exposed 14
Figure 7: L-CCRT™ Installed on one genset of UPY-2755, Genset #2 15
Figure 8: UPY2737 Setup for Baseline Testing by Combining All Three Exhaust Stacks 17
Figure 9: UPY-2755 equipped with 3 L-CCRT's. Exhaust Flow is combined for Part92b Testing 17
Figure 10: Part 92b PM emissions at each notch, for Baseline, 0-hour, 1500-hour and 3000-hour tests 19
Figure 11: PM Results (avg.) comparing the Tier 4 PM Locomotive Limit 20
Figure 12: Durability Notch Profile for UPY-2755..... 22
Figure 13: EGP at Notch-3 for zero-hour, 1500-hr and 3000-hr FTP tests, 95% C.I. error bars 23
Figure 14: EGP of Genset #3 before the incident and during the January 2013 sudden EGP increase..... 105

Acronyms and Abbreviations

ARB	California Air Resources Board
AQIP	Air Quality Improvement Program
CRT™	Continuously Regenerating Trap Filter
CARB	California Air Resources Board
C.I.	Confidence Interval
CRTdm	Onboard L-CCRT™ Diagnostic Monitoring System
DOC	Diesel Oxidation Catalyst
DPM	Diesel Particulate Matter
DPF	Diesel Particulate Filter
EGP	Exhaust Gas Pressure
EGT	Exhaust Gas Temperature
EPA	United States Environmental Protection Agency
FTP	Federal Test Protocol, 40 CFR Part 92b Testing
JM-DAQ	Data Acquisition System installed with L-CCRT
L-CCRT™	Locomotive Catalyzed CRT™
NO	Nitric Oxide
NO2	Nitrogen Dioxide
NOx	Nitrogen Oxides
NREC	National Railway Equipment Co.
OEM	Original Equipment Manufacturer
obs.BSFC	Observed Brake Specific Fuel Consumption
PGM	Platinum Group Metal
PM	Particulate Matter
PM2.5	Fine Particulate Matter; Particulate Matter 2.5 Micrometers in Diameter and Smaller
PM10	Particulate Matter 10 Micrometers in Diameter and Smaller
RPM	Rotations per Minute
SO_x	Sulfur Oxides
SWRI-LTC	Southwest Research Institute Locomotive Technology Center
TB Corr. PM	Tunnel Blank Corrected Particulate Matter Measurement (See Appendix A, page 39, paragraph 3)
UFP	Ultrafine Particle
U.S. EPA	United States Environmental Protection Agency
UPRR	Union Pacific Railroad Company
ULEL	Ultra-Low Emissions Locomotive

ACKNOWLEDGMENTS

The work reported in this document was partially funded by California Air Resources Board Air Quality Improvement Program (AQIP) under State of California Grant Number 09-AQIP-13, dated June 28, 2010. This project benefited from the participation of Ports of Los Angeles, Ports of Long Beach and Union Pacific Railroad, the other partners under this project. These companies provided management and coordination support to make this a successful project. The support of Union Pacific Railroad is especially appreciated.

EXECUTIVE SUMMARY

Johnson Matthey has developed proven technology to significantly reduce diesel particulate matter (PM) in both large stationary and mobile diesel engines. Use of an oxidation catalyst and a catalyzed particulate filter is the basis of this technology. This project tests a PM reduction after-treatment device on a 2007 Switcher Locomotive operated by Union Pacific (UPRR) in the Ports of Los Angeles and Long Beach, California.

The project objective is to demonstrate the emissions reduction performance and field service durability of a Johnson Matthey diesel particulate filter in a rail application. Subsequent to a successful completion of this project Johnson Matthey will apply for verification with the California Air Resources Board (CARB) as well as move forward with the commercialization of these systems. It is our intent to seek public financial incentives such as Carl Moyer, Proposition 1B, and other sources for switch locomotive projects in California and other locations in the US to assist in the commercialization process.

INTRODUCTION AND BACKGROUND

The purpose of this project was to demonstrate the Johnson Matthey Diesel Particulate Filter Technology so as to meet the 40 CFR Part 92b PM test cycle limit of 0.03 g/(bhp-hr) PM for switch locomotives equipped with diesel engines that have PM emissions of ≤ 0.2 g/(bhp-hr) during a 3000-hour durability period. Johnson Matthey installed the Locomotive-Continuously Regenerating Technology (L-CCRT™) DPF aftertreatment system on a Union Pacific Railroad Company (UPRR) UPY-2755 switch locomotive 3GS-21B ULEL, built by NREC. Since the locomotive consists of three (3) engine Gensets, as shown in Figure 1, three L-CCRT™ DPF systems were installed; one for each engine.

The L-CCRT™ DPF system is comprised of the following design features:

- L-CCRT™ Unit – Each L-CCRT™ Unit comprises a DOC upstream of a wall-flow DPF. They are close coupled to minimize volume.
- DOC – Each DOC is coated with platinum group metal (PGM) formulation to promote the conversion of a portion of the NO in the exhaust to NO_2, which in turn promotes the low temperature combustion of soot collected in the filter.
- L-CCRT™ System and Housing – Multiple L-CCRT™ Units are mounted in a single housing that is designed for easy access to the DOC and DPF's for routine cleaning and maintenance.
- The DPF also has a platinum group metal (PGM) formulation coating applied. The DOC removes CO and HC and oxidizes some of the NO in the exhaust gases to NO_2 This NO_2 then reacts with the PM trapped in the filter, producing NO and CO_2. Some of the NO is then reoxidized to NO_2 in the filter, which then reacts with more trapped PM. This enables the system to regenerate in applications with very low exhaust gas temperatures or low NO_x:PM ratios in the exhaust gases. Its major advantage is in its wider range of operating conditions.

The switcher provided by Union Pacific for this demonstration was a Model 3GS21B Ultra-Low Emissions Locomotive (ULEL) built by NREC. It is certified to the EPA's Tier 2 switch duty cycle standards. The N-ViroMotive switcher consists of three (3) QSK-19-700 Diesel Engine Gensets on skid mounted frames, as shown in Figure 1. This

locomotive is powered by three engine-driven generator sets, Model 572RDL. The 19 liter Cummins QSK19C engine is an in-line six cylinder configuration, turbocharged, air-to-air after-cooled, and is common rail injected. Each of the three engines is capable of developing 700 horsepower (522 kW) for a total locomotive power output of 2,100 horsepower (1,570 kW) with a nominal ISO 8178 D2 weighted PM emission factor of 0.2 g/(bhp-hr).

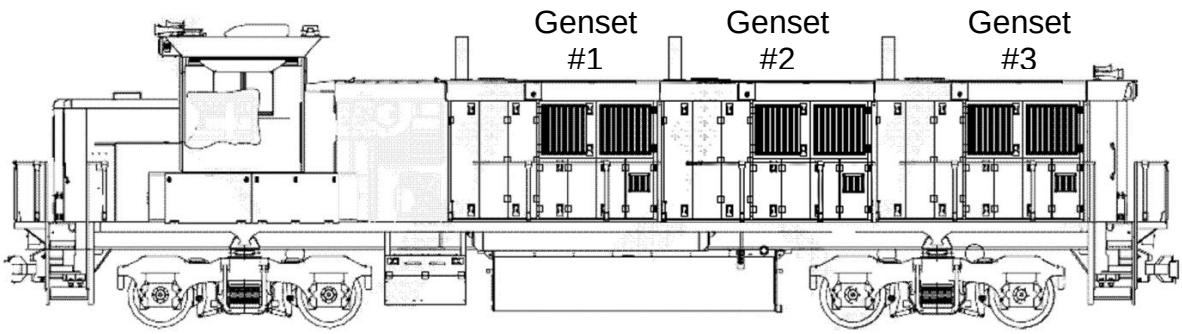


Figure: 1 Union Pacific UPY-2755 schematic of 3 GS-21B ULEL Switch Locomotive

PROJECT BUDGET

The proposed ARB grant agreement budget for this project is set at $692,356 with a contribution of $346,178 provided by the ARB. The participants, not to include ARB, are required to provide the other 50% of the total project expenses, as part of the agreement.

Table 1: Project Budget

Task No.	Task Name	Duration	Start	Finish	JM Project Costs	Project Admin Costs incurred by POLA	AQIP Project Funding Amount	AQIP Admin Funding Amount
	AB 118 Project - EPA Tier 4 PM Retrofit System	1088	12/10/2010	12/2/2013				
	Phase 1 - Installation and Zero-Hour Test of DPF System	111	12/10/2010	3/31/2011				
	Project Kickoff Meeting	1	12/10/2010	12/10/2010	$ 24,617.00	$ 10,000.00	$ 24,617.00	$ 10,000.00
1.1	Design DPF System	12	12/10/2010	12/22/2010				
1.2	Fabricate and install three DPF systems, one on each engine	88	12/23/2010	3/21/2011				
1.3	Analyze data and generate report	2	3/22/2011	3/24/2011				
1.4	**Deliverable: Initial test report after installing the DPF systems**	6	3/25/2011	3/31/2011	$ 86,544.00		$ 86,544.00	
	Phase 2-Durability Test of DPF System for 1500 Hrs	227	4/1/2011	11/14/2011				
2.1	Conduct 1500 hour field trial	206	4/1/2011	10/24/2011				
2.2	Test locomotive emissions per Part 92 and inspect DPF system	6	10/25/2011	10/31/2011				
2.3	Analyze data and generate report	5	5/15/2012	5/20/2012				
2.4	**Deliverable: Phase 2 Summary Report**	0	6/1/2012	6/1/2012	$ 86,545.00		$ 86,545.00	
	Phase 3 -Durability Test of DPF System for Remaining 1500 Hrs	348	6/1/2012	5/15/2013				
3.1	Conduct second 1500 hour field trial	348	6/1/2012	5/15/2013				
3.2	Test locomotive emissions per Part 92 and inspect DPF systems	31	3/15/2013	4/15/2013				
3.3	Analyze data and generate report	16	4/15/2013	5/1/2013	$ 86,545.00		$ 86,545.00	
3.4	**Deliverable: Phase 3 Summary Report (3000 Hrs)**	215	5/1/2013	12/2/2013	$ 41,927.00	$ 10,000.00	$ 41,927.00	$ 10,000.00
				TOTAL	$ 326,178.00	$ 20,000.00	$ 326,178.00	$ 20,000.00
			Project Total		**$346178**		**$346178**	

PROJECT TIMELINE

The scope of this project took place from December 2010 to the December 2, 2013. There were three phases in this project, which include installation, durability operations, and the completion of the verification period. During Phase 1, the after-

treatment system was installed, the initial emissions tests were completed, and the first durability period took place. After the first durability period of 1500 hours took place, Phase two began.

During Phase two, a 2nd FTP was completed to verify that the system continued to perform at PM reductions levels below the Tier 4 limit. After this was completed, a 2nd round of durability testing took place. Once the 2nd Phase was completed, the locomotive returned to Southwest Research Institute Locomotive Technology Center (SWRI-LTC) in order to complete the final round of FTP testing, Phase-3. After validating that the exhaust PM reduction met the Tier 4 Requirements, the project completed the main objective of this endeavor.

Due to some engine related malfunctions, the project schedule was pushed back to a completion date of December 2013, as compared to June 2013; see Appendix-C. The mechanical failures experienced during the demonstration have been deemed unrelated to the installation and independent of the use of the Johnson Matthey L-CCRT™ system DPF retrofit by Union Pacific mechanical staff. The new schedule, which included the project delays and new projections, is shown in Figure 2. At this point, all phases have been completed, and verification testing has successfully proven the performance of the L-CCRT™.

ID	Task Name	Start
1	**AB118 Project - EPA Tier 4 PM Retrofit System**	**Tue 11/16/10**
2	***Pre-Project Readiness***	**Tue 11/16/10**
15	Project Kickoff Meeting	Fri 12/10/10
16	***Phase 1A - Installation and Zero-Hour Test of DPF System***	**Fri 12/10/10**
21	Zero-Hour locomotive Test, emissions per Part 92	Fri 5/27/11
22	Analyze data and generate report	Mon 6/6/11
23	**Deliverable 1: Zero-Hour test report of DPF System**	Thu 6/9/11
24	***Phase 1B-Durability Test of DPF System for 1500 Hrs***	**Thu 6/23/11**
25	Transport locomotive to CA	Thu 6/23/11
26	Conduct 1500 hour field trial	Wed 7/6/11
27	Transport Locomotive to test facility (SWRI-TX)	Mon 3/12/12
28	Test locomotive emissions per Part 92 and inspect DPF systems	Fri 3/23/12
29	Analyze test data and generate report	Mon 4/30/12
30	**Deliverable2: Phase 2 Summary Report (1500 Hrs)**	Mon 10/15/12
31	***Phase 2 -Durability Test of DPF System for Remaining 500-1500 Hrs***	**Mon 4/30/12**
32	Transport locomotive to CA	Mon 4/30/12
33	Conduct 500 to 1500 hour field trial	Wed 5/9/12
34	Transport Locomotive to test facility (SWRI-TX)	Mon 3/18/13
35	Test locomotive emissions per Part 92 and inspect DPF systems	Mon 3/25/13
36	Analyze test data and generate report	Wed 8/7/13
37	**Deliverable: Phase 3 Summary Report (3000 Hrs)**	Mon 11/4/13
38	**Submit Final Disbursement Request**	Mon 11/25/13

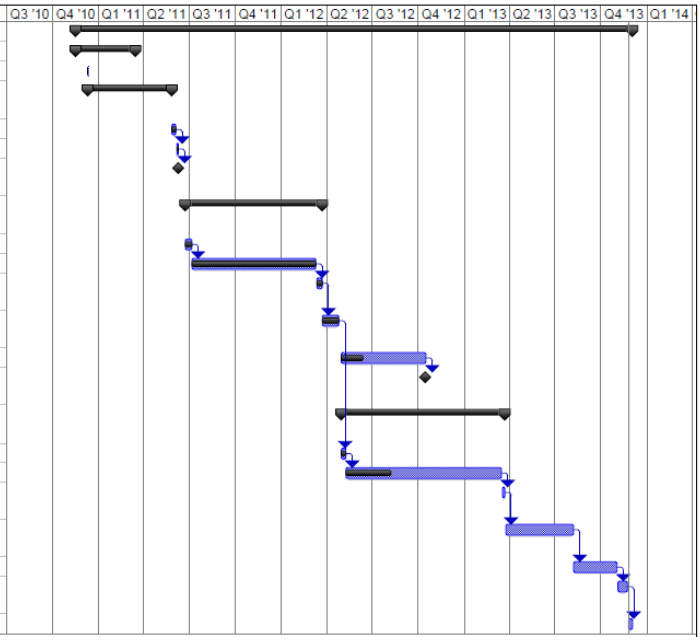


Figure 2: Project Timeline

The 3000-hour 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, were performed on 4/12/13, 04/15/13 and 08/06/13. The durability operation of the locomotive began on 6/23/11, as it was picked up from the Southwest Research Institute Locomotive Technology Center (SWRI-LTC) and transported to the Union Pacific Railroad Company (UPRR) Mead Yard in Wilmington, California. The accumulation of 3000 hours was completed on 03/13/13. The rate of accumulation of the 3000-hours between those dates is presented in Figure 3.

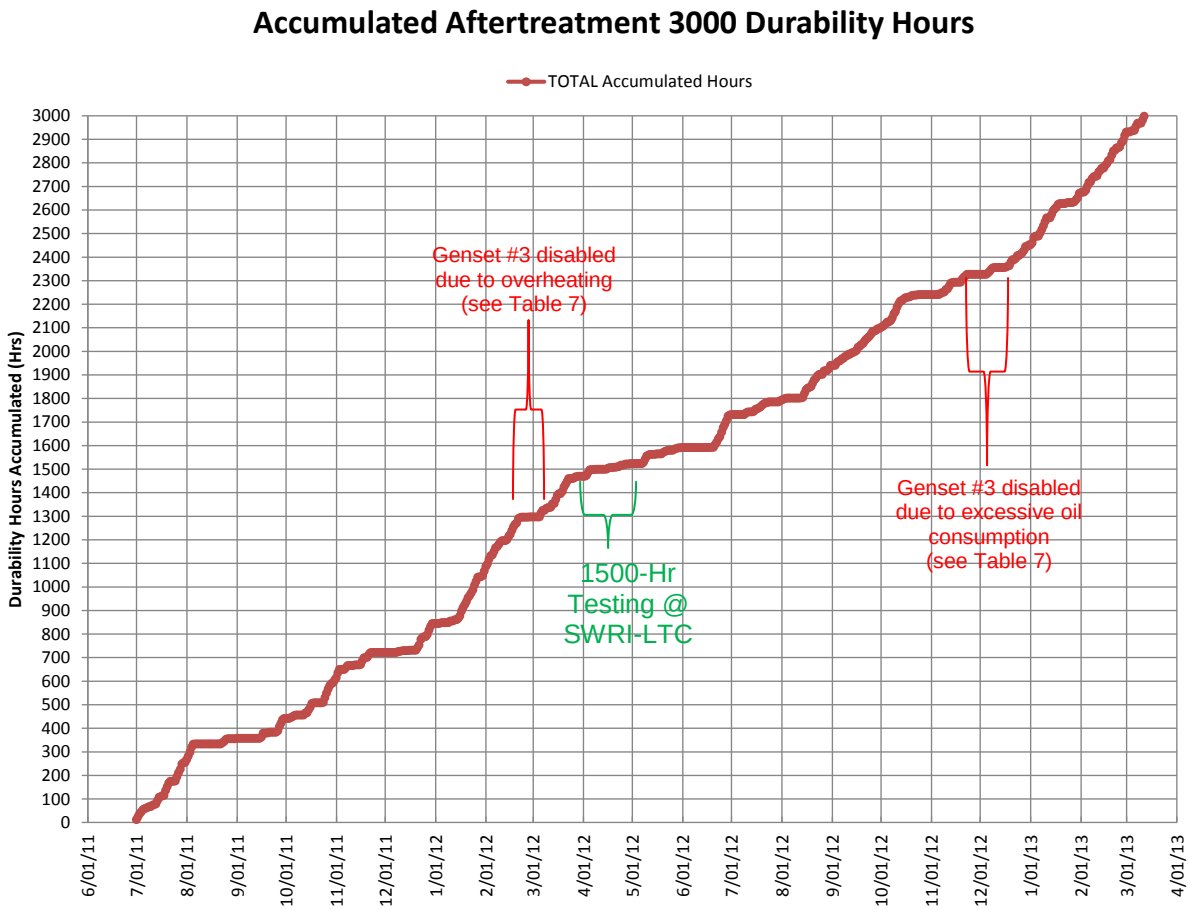


Figure 3: Durability Hour Accumulation for 3000 Hour Durability Period

While conducting the normal durability operations in the Los Angeles Basin, Engine #3 was disabled due to a malfunction that caused the engine cooling system to exceed its normal operating temperature, see Appendix G for the repair report. The initial malfunction was reported on February 20, 2012. Since the locomotive had accumulated 1300 hours at the time of the malfunction, a decision was made to disable the Genset #3 for the remainder of the first durability period and to run the switch locomotive on Gensets #'s 1 and 2. Once the durability period was completed, the locomotive was moved to the SWRI-LTC (203 Milam Street San Antonio, TX 78202) for repairs and follow on 1500-hour FTP testing. The root cause of the malfunction was observed to be a defect in the casting of the #5 cylinder head intake port of the engine.

While conducting an inspection of the L-CCRT™ it was found that no significant impact was imparted to the system during the malfunction of the engine. Further, after the engine repairs were completed the Genset #3, with the L-CCRT™ installed, was run and monitored for back-pressure and temperature. Results of this preliminary test found that all performance parameters were within normal operation, and further validated the engine repairs and the normal operation of the DPF system.

Once the 1500-hour Test was completed, the 2nd part of the 3000-hour durability period of the Locomotive Verification Plan began. During this 2nd durability period, the locomotive returned to revenue service in Southern California's LA Basin and carried out a second 1500 hour period of service. During this second period, an engine malfunction caused the temporary removal of the switch locomotive from service, at about 2600 hours

of durability service, and an inspection of the L-CCRT filters ensued. It was found that during periodic maintenance of the switch locomotive, i.e. federally mandated 90 day regular maintenance, oil was overfilled in the oil sump, causing excess oil consumption to be ingested into the combustion system, and causing an accelerated L-CCRT™ Filter backpressure increase. This effect was isolated to Genset #3, and is described in more detail in Appendix H of this report. After inspection of the filters and catalyst elements, it was found that unburned hydrocarbons and an excess level of soot accumulation on the face of these elements was exhibited. Inspection of the L-CCRT™ filters of Genset #1 and 2 found normal conditions, as was indicated by the backpressure monitoring trend. After meeting with the members of the AQIP project, it was agreed that the filters and catalyst elements could be cleaned via CARB approved cleaning methods. However, a detailed report of the malfunction would be needed to determine the root cause of the malfunction, as detailed in Appendix H. After the filters and catalyst elements were cleaned, and the engine was repaired, the switch unit was re-assembled and returned to revenue service.

The locomotive returned to the SWRI-LTC to carry out the final triplicate set of Part 92b tests on April 4th, 2013. The purpose of these follow up tests was to verify the L-CCRT™ system performance after the 3000 hours of revenue service-environment of the switch locomotive. The 3rd Part 92b tests resulted in PM output emissions lower than the Tier 4 Switch Locomotive EPA Limits and the L-CCRT™ DPF system met the objectives of the project.

PROJECT MILESTONES

The project milestones are enumerated below. These milestones reflect the major events in the project, as well as the expected outcomes. All milestones were completed.

1. Design DPF System

The test locomotive will be inspected and measured to determine the size, shape, mounting details, and exhaust piping arrangement for the DPF system. At least one Johnson Matthey engineer and one electrical engineer will inspect the locomotive and take dimensional measurements. They will return to the home office and design the emission control system including electronic controls. The DPF system will be custom designed to fit the available space in the locomotive and provide the PM reduction required to meet Tier 4 standards while meeting the exhaust back pressure limit and expected 6 month cleaning interval. - **COMPLETED**

2. Fabricate and install three DPF systems, one on each engine

Johnson Matthey will create the custom fabrication drawings and electrical schematics for the DPF system. The electro-mechanical hardware will be fabricated and then shipped to SwRI. SwRI will be contracted to install the DPF systems. The existing silencers will be removed from the engine exhaust systems and replaced with the DPF systems. The roof of the locomotive will be modified to fit the DPF systems. - **COMPLETED**

3. Test locomotive emissions per Part 92 – “Zero Hour Test”

The locomotive stacks will be combined and the common exhaust pipe will be connected to analytical equipment and the exhaust will be analyzed to determine treated emissions levels for CO, NOx, PM, exhaust temperatures, and flow rates. Prior to testing, a 20-hour degreening phase will take place, in order to thermally stabilize the catalyst performance

(Knafl, 2006). The locomotive will be tested according to EPA CFR Title 40 Part 92 test methods. - **COMPLETED**

4. Analyze data and generate report

The SwRI data will be analyzed and presented in the initial report. Baseline emissions will be calculated and reported with the EPA switch locomotive duty cycle weighting applied. - **COMPLETED**

5. Deliverable: Initial test report after installing the DPF systems

- **COMPLETED**

6. Conduct 1500 Hour field trial

The locomotive will be released to UP. UP will send the locomotive to California for field testing. During the field trial, Johnson Matthey will monitor the exhaust system back pressure, exhaust temperature, and duty cycles with a cell based data acquisition system.

- **COMPLETED**

7. Test locomotive emissions per Part 92 and inspect DPF system.

The locomotive will be returned to SwRI and the locomotive exhaust stacks will be connected to analytical equipment and the exhaust will be analyzed to determine emissions levels for CO, NOx, PM, exhaust temperatures, and flow rates. The engine will be tested according to EPA CFR Title 40 Part 92 test methods. The DPF system will be visually inspected to determine if electrical controls and mechanical hardware, including filters and catalyst, are still intact with no damage, loose components, corrosion, etc. A JM engineer will perform the visual inspection.

- **COMPLETED**

8. Analyze test data and generate report

The SwRI data including results of the visual inspection will be presented in the final Phase 1 summary report.

- **COMPLETED**

9. Deliverable: Phase 1 Summary Report

- **COMPLETED**

10. Conduct second 1500 Hour field trial

The locomotive will be released to UP. UP will send the locomotive back to California for additional field testing. During the field trial, Johnson Matthey will monitor the exhaust system back pressure, exhaust temperature, and duty cycles with a cell based data acquisition system.

- **COMPLETED**

11. Test locomotive emissions per Part 92 and inspect DPF systems

The locomotive will be returned to SwRI and the test engines will be connected to analytical equipment and the exhaust will be analyzed to determine emissions levels for CO, NOx, PM, exhaust temperatures, and flow rates. The engines will be tested

according to EPA CFR Title 40 Part 92 test methods. The DPF systems will be visually inspected to determine if electrical controls and mechanical hardware, including filters and catalyst, are still intact with no damage, loose components, corrosion, etc. A JM engineer will perform the visual inspection.

- **COMPLETED**

12. Analyze test data and generate report

The SwRI data including results of the visual inspection will be presented in the final Phase two summary report. 3000 hour emissions will be calculated and reported with the EPA switch locomotive duty cycle weighting applied.

- **COMPLETED**

13. Deliverable: Phase Two Summary Report and Final Report

- **COMPLETED**

AFTER-TREATMENT INSTALLATION

The L-CCRT Installation began on April 2011 and was competed on May 20, 2011. The installation of the 3 L-CCRT's is shown in Figures 4 and 5, below; which show the locomotive UPY-2755 before and after the retrofit installation.

Figure 4: Union Pacific Switch Locomotive UPY-2755 fully equipped with 3 L-CCRT's

Figure 5: Union Pacific Switch Locomotive UPY-2755 in original state

Description of Locomotive CCRT (L-CCRT)

The installation of the L-CCRT's required modification to the engine skid on each of the three Gensets, as shown in Figure 6. The removal of the original engine muffler provided the necessary space to install the unit.

Figure 6: L-CCRT Installed on one Genset of UPY-2755, with Engine Exposed

The design of the L-CCRT is intended to operate in a harsh mechanical environment. The mounting design takes into consideration the following:

1. High G-Shock loads related to the switcher coupling during normal revenue service. The design is expected to sustain a high-cycle of 5-G-Shock loads.
2. The High temperature environment (~1050 °F) of the engine exhaust will result in large thermal expansion of the unit during operation. This type of growth was accounted for, and is expected to work in tandem with the 5-G-Shock load rating, as described above.

Figure 7: L-CCRT™ Installed on one genset of UPY-2755, Genset #2

It is expected that the filter element of the L-CCRT DPF System will have to be periodically cleaned of collected ash. The cleaning can be carried out by removing the top lid of the housing to gain access to the filters, see Figure 7. The period between cleanings is dependent on how much lubricating oil the engine burns and the number of hours of operation in idle mode.

Johnson Matthey's best estimate for cleaning cycle for locomotive engine operation is somewhere between 4100 and 6000 hours of service depending on the operational performance of the engines. While this is a broad range for a cleaning frequency, the actual cleaning frequency for each engine can be determined from the Onboard L-CCRT™ Diagnostic Monitoring System (CRTdm). The CRTdm monitors the genset's engine exhaust-gas-pressure (EGP) and exhaust temperature (EGT). Once the EGP gets to within 90% of the maximum operating limit, an amber warning light is emitted to inform the operator of the maintenance requirement. Once 100% of the maximum operating limit

is achieved, a red warning light is emitted to inform the operator to stop the use of the genset until maintenance is completed.

3000-Hour EVALUATION RESULTS

The locomotive engine test procedure is designed to determine the brake specific emissions of particulates, as per 92.123 of 40 CFR Part 92 Subpart B. The test procedure consists of measurements of brake specific emissions at each throttle position as engine power is increased. Since there are three engines in this locomotive, an exhaust collector was fabricated to join the exhaust to a single output, as shown in Figures 8 and 9. The regulations require three tests be repeated as shown in Table 2, below. The sample times for all the test modes was increased to 600 seconds, versus the minimum of 360 seconds, in order to acquire a measurable amount of particulate matter for each test.

Exhaust emissions testing for this project was performed by Southwest Research Institute at the SwRI-LTC in San Antonio, Texas. SwRI performed baseline exhaust emission tests using the FTP for locomotives, as detailed in Title 40 of the U. S. 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. Since the switch locomotive is not equipped with a dynamic brake, Mode Numbers 1, 1a, and 2 are equivalent.

Table 2: Test sequence for locomotives and locomotive engines
B124–1 of 40 CFR Part 92 Subpart B Section 92.124

Mode No.	Notch setting	Time in notch	Emissions measured	Power, and fuel consumption measured
Warm up	Notch 8	5 ±1 min	None	None
Warm up	Lowest Idle	15 min maximum (after engine speed reaches lowest idle speed)	None	None
1a	Low Idle	6 minutes minimum (600 seconds actual)	All	Both
1	Normal Idle	6 minutes minimum (600 seconds actual)	All	Both
2	Dynamic Brake	6 minutes minimum (600 seconds actual)	All	Both
3	Notch 1	6 minutes minimum (600 seconds actual)	All	Both
4	Notch 2	6 minutes minimum (600 seconds actual)	All	Both
5	Notch 3	6 minutes minimum (600 seconds actual)	All	Both
6	Notch 4	6 minutes minimum (600 seconds actual)	All	Both
7	Notch 5	6 minutes minimum (600 seconds actual)	All	Both
8	Notch 6	6 minutes minimum (600 seconds actual)	All	Both
9	Notch 7	6 minutes minimum (600 seconds actual)	All	Both
10	Notch 8	15 min minimum	All	Both

Figure 8: UPY2737 Setup for Baseline Testing by Combining All Three Exhaust Stacks

In order to simplify the timeline for this project, the locomotive baseline emissions test results for UPY-2737 were used. Under CARB Agreement No. 08-409, SWRI-LTC was contracted to perform a baseline emission test on a UPRR provided switcher locomotive UPY2737. The locomotive baseline testing, with all three engine gensets active, followed Title 40 of the U. S. CFR, Part 92, Subpart B. This locomotive, UPY-2737, is of the same series of locomotives as UPY-2755, including the same series QSK-19-700 Engines. The testing for UPY-2737 took place in January 2010. Since the switch locomotive model and engines are of the same series, the differences between the two FTP tests should be minimal. During the baseline emissions testing of UPY-2737, the exhaust stacks of all three engines were combined to a single plenum, as shown in Figure 8. The purpose of the January 2010 test was to determine the output emissions from the switch locomotive without an aftertreatment device. The results for the baseline tests are shown in Table 3.

Figure 9: UPY-2755 equipped with 3 L-CCRT's. Exhaust Flow is combined for Part92b Testing

In addition to the baseline test results, the zero-hour, 1500-hundred hour and 3000-hour results from phases 1 and 2 are presented in Table 3, and graphically displayed in Figure 10. The PM outputs in all tests were well below the Tier 4 PM Limit of 0.03 g/(bhp-hr). The final PM values are displayed under the 8th column under PM (g/hp-hr).

Table 3: FTP Results for Baseline, 0-hour, 1500 Hour and 3000 Hour Tests

			CFR 40 Part 92b EPA Switch Cycle					
			obs.BSFC	HC	CO	NOx	PM	TB Corr. PM
Date	Fuel	Test	lb/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr
BASELINE FTP TEST RESULTS FOR UPY-2737 without an After-treatment System								
22-Jan-10	TxLED-ULSD	FTP-1	0.412	0.13	1.26	2.9	0.108	
25-Jan-10	TxLED-ULSD	FTP-2	0.414	0.12	1.21	3.0	0.100	
25-Jan-10	TxLED-ULSD	FTP-3	0.426	0.13	1.26	3.0	0.107	
	Average Engine Out (Baseline UPY-2737)		0.417	0.128	1.2410	3.0	0.105	
ZERO HOUR FTP TEST RESULTS FOR UPY-2755 with L-CCRT© DPF System								
3-Jun-11	EPA Cert ULSD	FTP-1	0.402	0.02	0.00	2.7	0.004	0.002
3-Jun-11	EPA Cert ULSD	FTP-2	0.403	0.01	0.00	2.8	0.003	0.001
4-Jun-11	EPA Cert ULSD	FTP-3	0.423	0.01	0.00	2.6	0.003	0.002
	Average JM-DPF (UPY-2755)		0.409	0.014	0.0041	2.7	0.003	0.002
	Engine Out avg vs. JM-DPF, % diff		-1.93%	-97%	-100%	-8%	-97%	-99%
1500 HOUR FTP TEST RESULTS FOR UPY-2755 with L-CCRT© DPF System								
24-Apr-12	EPA Cert ULSD	FTP-1	0.417	0.03	0.00	3.0	0.007	0.006
24-Apr-12	EPA Cert ULSD	FTP-2	0.408	0.01	0.00	2.8	0.011	0.008
27-Apr-12	EPA Cert ULSD	FTP-3	0.418	0.03	0.00	2.6	0.011	0.010
	Average JM-DPF (UPY-2755)		0.414	0.021	0.0038	2.8	0.010	0.008
	Engine Out avg vs. JM-DPF, % diff		-1%	-83%	-100%	-5%	-91%	-92%
3000 HOUR FTP TEST RESULTS FOR UPY-2755 with L-CCRT© DPF System								
12-Apr-13	EPA Cert ULSD	FTP-1	0.425	0.01	0.01	2.8	0.022	0.022
15-Apr-13	EPA Cert ULSD	FTP-2	0.434	0.01	0.01	2.8	0.019	0.017
5-Aug-13	EPA Cert ULSD	FTP-3	0.421	0.02	0.00	3.0	0.022	0.020
	Average JM-DPF (UPY-2755)		0.427	0.01	0.01	2.9	0.021	0.019
	Engine Out avg vs. JM-DPF, % diff		2%	-90%	-99%	-3%	-80%	-82%

Due to the low PM output from the L-CCRT™ system, it was noticed that a slight accumulation of PM was deposited onto the surface of the test plenum, interior surfaces, and ducts used to measure the PM output. As such, a test was carried out to measure the PM released from these surfaces after the locomotive was turned off. The PM measured from this test was found to be a slight but significant percentage of the overall PM found during the test outlined in Table 2. Thus, the Tunnel Background Corrected Particulate Matter (TB Corr. PM) in column 9 was determined to be the PM measured minus the PM found during the post PM test measurements, see Appendix-A, pg. 39, Section 2.5.2 Particulate Emissions Sampling for a more detailed description.

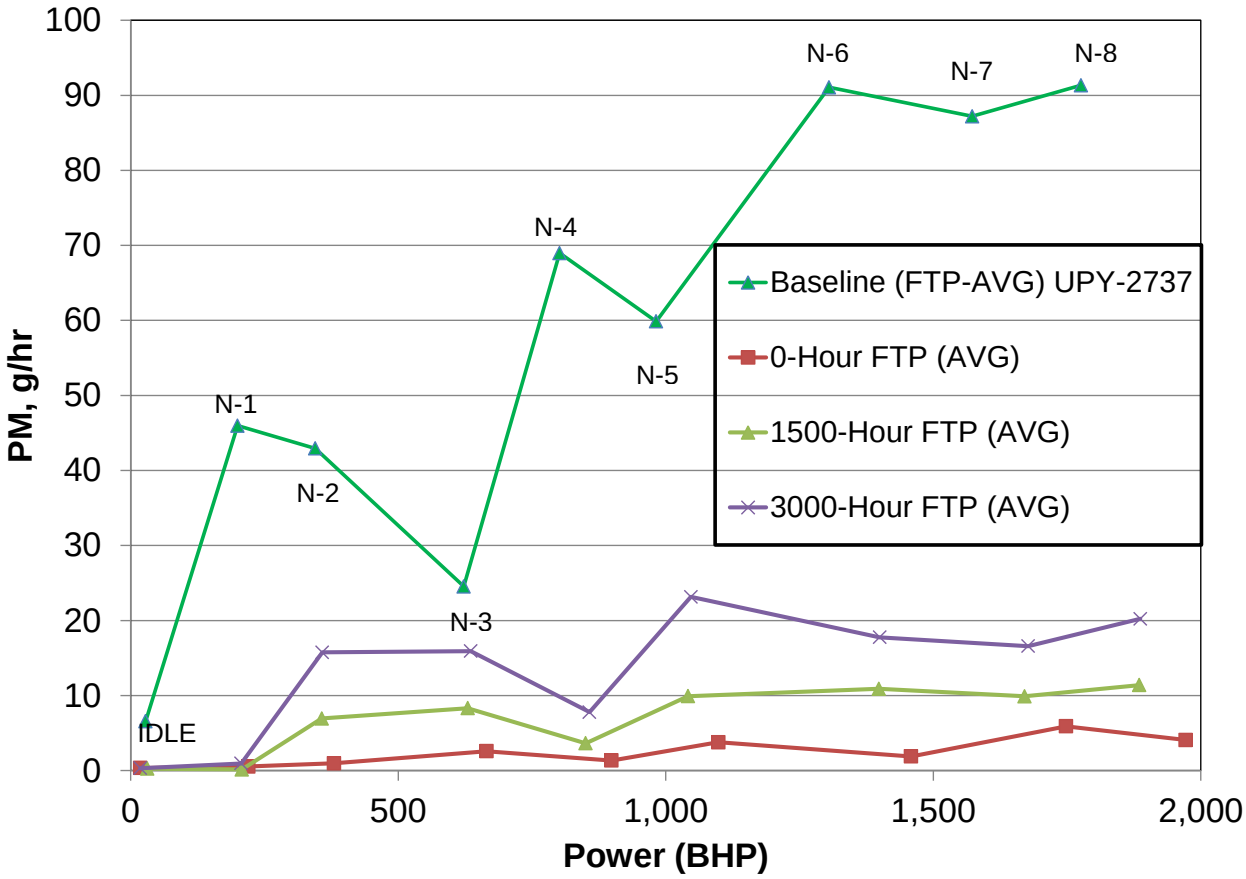


Figure 10: Part 92b PM emissions at each notch, for Baseline, 0-hour, 1500-hour and 3000-hour tests

The comparison of the baseline emissions tests and the 3000-hour Tests demonstrated a PM reduction of greater than 80%, or a switch cycle weighted output PM of 0.021 g/(bhp-hr). Given the EPA Tier-4 Switcher Cycle Output PM limit of 0.03 g/(bhp-hr), the results of this test showed that the locomotive PM emissions were about 30% below the Tier-4 PM Limit, as shown in Figure 11. As shown in Figure 10, the PM output at each notch was significantly reduced. The Observed Brake Specific Fuel Consumption (obs.BSFC) in column 4 of Table 3 is representative of the fuel consumption of the locomotive during normal operation. As shown in Appendix A's figure 8, there was no statistically significant change in fuel consumption throughout the 3000 hours of durability service.

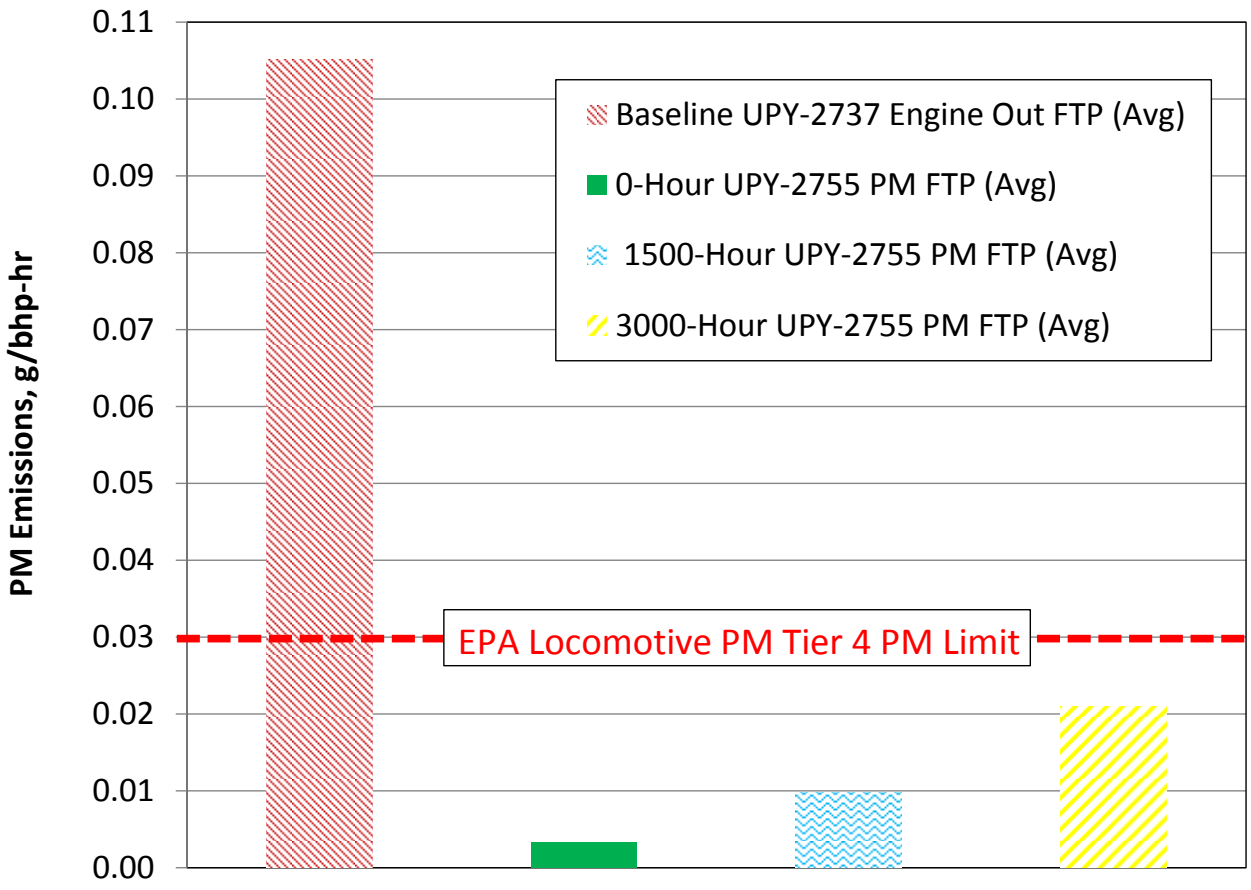


Figure 11: PM Results (avg.) comparing the Tier 4 PM Locomotive Limit versus the Baseline Engine Out, the 0-hour Results, 1500-hour and the 3000-hour Results

3000 HOUR DURABILITY PERIOD AND PERFORMANCE

During the durability period, a data acquisition system (JM-DAQ) monitored the system back-pressure, EGP, engine exhaust temperature, EGT, and engine RPM. The purpose of this data collection is to monitor the day-to-day performance of the after-treatment system.

Table 4: NREC Rated Power at each Notch Setting

COMPANY CONFIDENTIAL INFORMATION

Given the locomotive OEM performance specifications, as provided by the manufacturer, NREC, in Table 4, it was possible to determine the time spent at each locomotive notch position, and therefore determine important durability information, as presented in Table 5.

Table 5: Estimated Performance of UPY-2755 during the 3000 hour durability operation

COMPANY CONFIDENTIAL INFORMATION

Further, the data presented the notch-profile of the locomotive during the 3000-hour operational period, as shown in Figure 12.

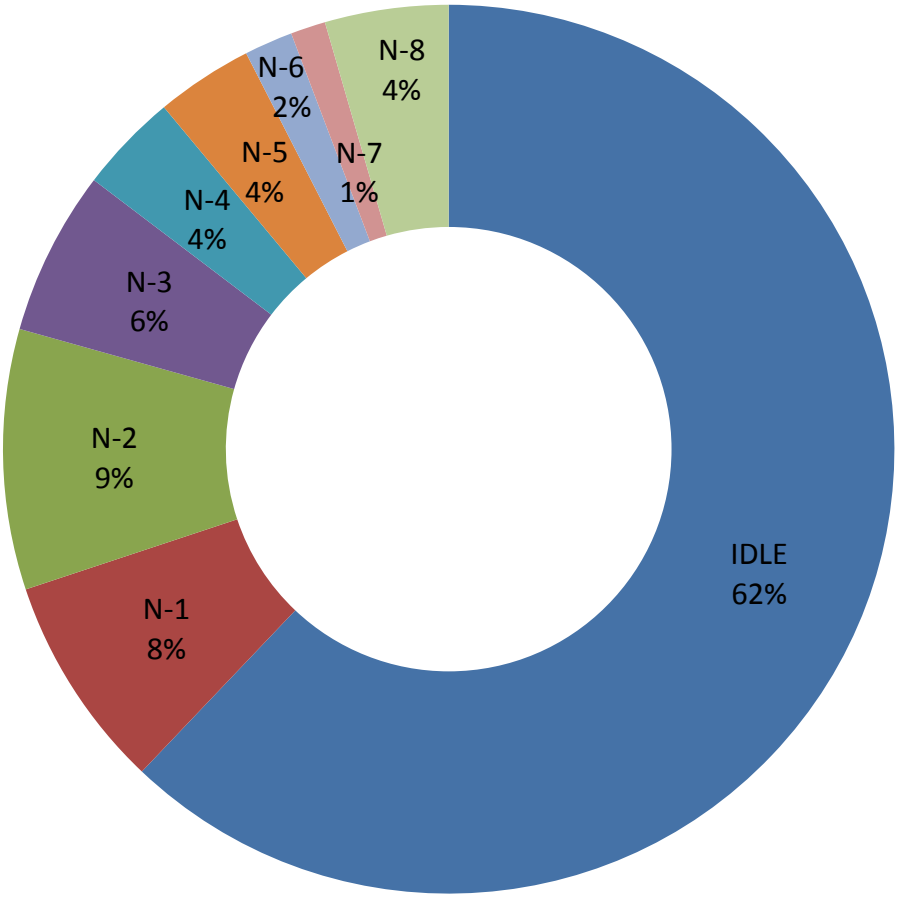


Figure 12: Durability Notch Profile for UPY-2755

The pie chart in Figure 12 demonstrates that a large part of the operational cycle of the switch locomotive is spent in the Idle state. Further, a full eighty percent of the time the operational duty cycle is spent in Idle, Notch-1 and Notch-2.

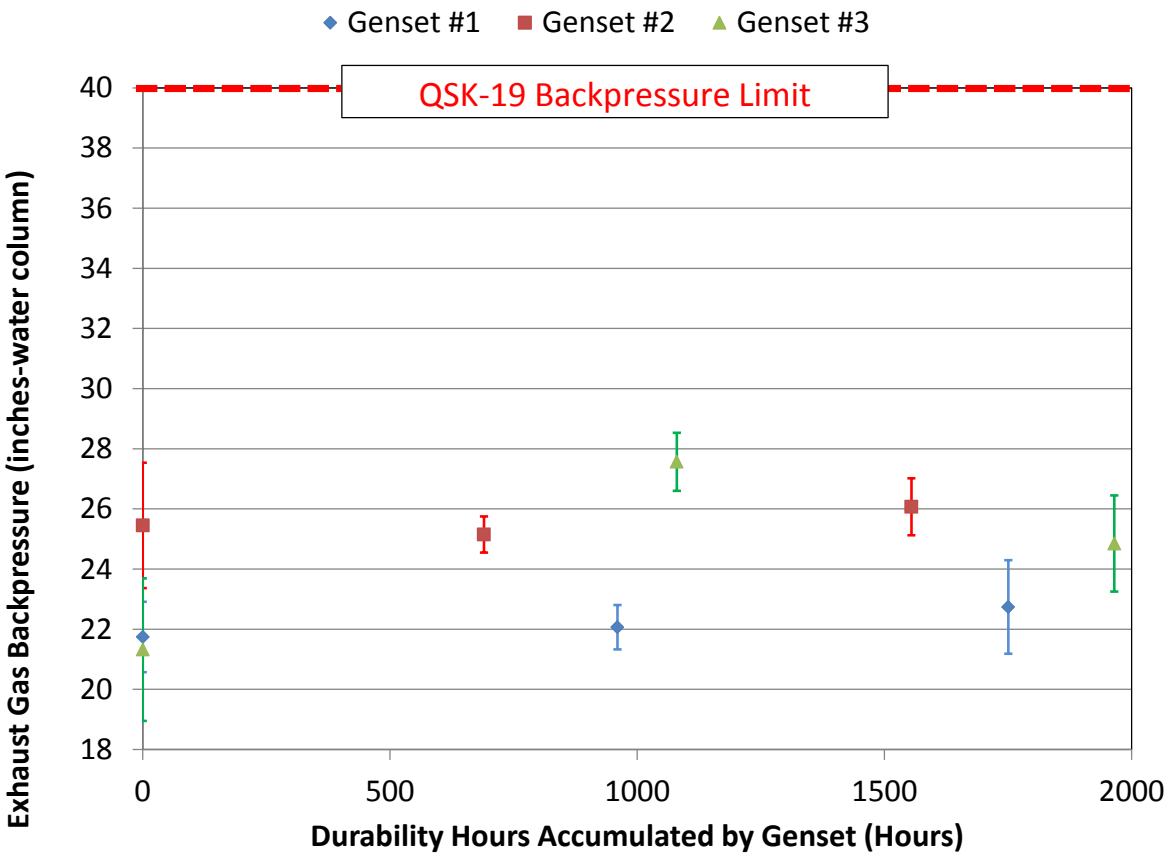


Figure 13: EGP at Notch-3 for zero-hour, 1500-hr and 3000-hr FTP tests, 95% C.I. error bars

Test data taken during the FTP cycle at SWRI-LTC was used to determine the performance of the system at both the zero-hour and 1500 hour periods. The overall performance of the DPF system remains within the normal operating EGP of the aftertreatment system, i.e. less than 40 inches of water column pressure. One important test point demonstrating the health of the individual genset system is the Exhaust Gas Pressure, EGP, of the L-CCRT™ at the Notch-3 position.

Table 6: Notch-3 EGP FTP Results

ENGINE	DATE	DURABILITY TIME	NOTCH	EGP (Avg)	EGP (σ)
#	#	Hours	#	" W.C.	" W.C.
1	7/27/2011	0	3	21.7	1.0
2	6/3/2011	0	3	25.5	1.2
3	5/27/2011	0	3	21.3	0.6
1	4/24/2012	960	3	22.1	0.3
2	4/24/2012	690	3	25.2	0.5
3	4/27/2012	1080	3	27.6	0.4
1	8/5/2013	1750.5	3	22.7	0.5
2	4/12/2013	1554.5	3	26.1	0.8
3	4/13/2013	1964.9	3	24.8	0.8

At Notch-3, a single genset is activated and is operating at 98% of the full capacity of the engine. The data taken during the zero-hour, 1500-hour and 3000-hour testing was compared at this test point, and is presented in Figure 13 and Table 6. Since data was collected from each of the systems independently, it was possible to determine the individual run time of each Genset, despite the combined locomotive run time of 3000 hours. During previous baseline testing on UPY-2737, it was found that the EGP of the Gensets with the OEM silencer was 37"W.C. (inches of water column). However, as shown in Figure 13 and Table 6, the EGP of the three L-CCRT™'s ranged from 22.7 to 27.6"W.C. after 3000 hours of service.

CONCLUSIONS

The Johnson Matthey L-CCRT™ diesel particulate filter technology demonstrated significant reductions in FTP Switch cycle HC, CO and PM emissions on locomotive UPY-2755 after 3000 hours of field durability operation. The overall PM output after the 3000-hour durability period was 0.021 g/(bhp-hr), or about 30% below the EPA Tier-4 Switch Duty cycle limit of 0.03 g/(bhp-hr) and 71% below the Baseline Output Emissions.

After 3000 hours of service, the performance of the L-CCRT system did not degrade in any significant manner. Despite exposure to the high-cycle 5-g shock loading mechanical environment, the robust design allowed the system to perform as expected, resulting in PM emissions being below the Tier 4-PM limit throughout the project.

Johnson Matthey's L-CCRT™ DPF technology achieved Tier 4 PM emission limits on a three genset switch locomotive. The L-CCRT™ DPF system was demonstrated through this project to be reliable and durable over three years of field operation. With this success, it is our intention to commercialize the L-CCRT™ for use on switch locomotive applications**.**

With the successful completion of the project, it is our intention to commercialize the L-CCRT™ system as a retrofit device on the existing installed base of switch locomotive applications in California and elsewhere in the US.

We have begun the process of applying for verification with the California Air Resources Board (CARB) and anticipate that the L-CCRT™ will receive CARB verification in the first quarter of 2014.

We will apply for public financial incentives in California such as Carl Moyer and Prop 1B as well as other public funding sources outside of California for projects elsewhere in the US. These public Incentive funds will be used to assist in the commercialization of this technology to incentivize owner operators of genset switch locomotives to reduce emissions wherever these locomotives are located.

REFERENCES

1. National Railway Equipment Co. (NREC). N-ViroMotive 3GS-21B ULEL Switcher. <http://www.nationalrailway.com/3GS-21B_Spec%20ad.pdf>
2. Knafl, A. "Characterizing Light-Off Behavior and Species-Resolved Conversion Efficiencies During In-Situ Diesel Oxidation Catalyst Degreening." SAE 2006 World Congress & Exhibition (2006)

APPENDIX A: SWRI 3000-hour Test Report

NREC 3GS21B Gen Set Locomotive DPF Verification Testing

FINAL REPORT

SwRI Project No. 03.16478 and 03.16482

Prepared For

Johnson Matthey Stationary Emissions Control, LLC
900 Forge Avenue, Suite 100
Audubon, PA 19403-2305

Prepared by

Steven G. Fritz, P.E.
and
John C. Hedrick

SOUTHWEST RESEARCH INSTITUTE
P.O. Drawer 28510 6220 Culebra Road
San Antonio, TX 78228-0510

November, 2013

SOUTHWEST RESEARCH INSTITUTE®
SAN ANTONIO, TX • HOUSTON, TX • ANN ARBOR, MI • WASHINGTON, DC

NREC 3GS21B Gen set Locomotive DPF Verification Testing

FINAL REPORT

SwRI Project No. 03.16478 and 03.16482

Prepared For

Johnson Matthey Stationary Emissions Control, LLC
900 Forge Avenue, Suite 100
Audubon, PA 19403-2305

November, 2013

Prepared by:

John C. Hedrick, Principal Scientist
Medium Speed Diesel Engines
Department of Emissions R&D

Steven G. Fritz, Manager
Medium Speed Diesel Engines
Department of Emissions R&D

Approved by:

Jeff J. White, Director
Department of Emissions R&D

DEPARTMENT OF EMISSIONS R & D
ENGINE, EMISSIONS AND VEHICLE RESEARCH DIVISION

This report shall not be reproduced, except in full, without the written approval of Southwest Research Institute®.
Results and discussion given in this report relate only to the test items described in this report.

EXECUTIVE SUMMARY

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.

On May 28, 2010, the City of Los Angeles Harbor Department and the Port of Long Beach jointly submitted a proposal to CARB for AB118 AQIP Advanced Technology Demonstration grant funding to demonstrate a Tier 4 locomotive Diesel Particulate Filter (DPF) retrofit system on a 2,100 HP genset switcher locomotive. The project partners included Johnson Matthey, Inc., the technology provider, and Union Pacific Railroad, which used the retrofit system on a switching locomotive operating in the San Pedro Bay Ports.

The test locomotive used for this project was UPY2755, a NREC model 3GS21B originally manufactured in July 2007. This locomotive uses three diesel-engine driven generator sets (Gen Set 1, 2, and 3) to provide power to the locomotive traction motors.

The JM L-CCRT DPF retrofit aftertreatment system uses a active diesel oxidation catalyst (DOC) in front of the DPF. The DOC converted NO to NO_2 to help oxidize the PM accumulated in the DPF to continually regenerate the filter, which limits the back pressure on the engine.

UPY2755 was modified to fit the three JM L-CCRT DPF housings, in place of the standard mufflers for each of the three engines. While the L-CCRT DPF housing is roughly the same footprint as the muffler, the L-CCRT DPF housing is taller than the stock muffler, which requires the roof sections of the locomotive over the engines to be modified to accept the taller L-CCRT DPF housing. Additionally the mounting system of the L-CCRT housing was significantly different than the stock muffler, which required a number of modifications to the mounting plate that is directly over the engines.

Exhaust emissions measurements followed Title 40 of the U. S. Code of Federal Regulations (CFR), Part 92, Subpart B for all locomotive tests. To meet the Part 92 emissions requirements, the three exhaust systems were combined into a common manifold so that the exhaust sample could be taken from the combined exhaust flow.

During the zero hour testing of the L-CCRT DPF assembly performed in June 2011, the HC emissions were reduced by 89 percent and essentially eliminated CO emissions. The JM L-CCRT DPF system caused no significant change in the Switch Cycle weighted fuel consumption or NO_X emissions. Compared to the UPY2737 engine-out baseline, PM emissions were reduced

by 97 percent to 0.003 g/hp-hr, 90 percent below the locomotive Tier 4 PM limits that go into effect for new locomotives in 2015.

The 1,500 hour emission test conducted in April 2012 showed that the JM L-CCRT DPF performing well, with average EPA Switch Cycle PM emissions at 0.010 g/hp-hr. This PM level was higher than the 0-hour PM, changing from 90 percent below the Tier 4 limits at 0-hours to 68 percent below the Tier 4 PM limits at 1500-hours. Compared to the UPY2737 engine-out baseline, the PM reduction changed from 97 percent at 0-hours to 91 percent at 1500-hours.

The final test at 3,000 hours of operation was conducted in April 2013 and these tests showed that the EPA Switch Cycle PM emissions had increased to 0.021 g/hp-hr, or 30% below the Tier 4 PM level, and a PM reduction of 80 percent compared to the UPY2737 baseline engine-out emissions. The CO and HC emissions remained very low for both the 1,500 and 3,000 hour tests.

ACKNOWLEDGMENTS

The work reported in this document was funded by Johnson Matthey and California Air Resources Board as part of a California AB118 project for a 3,000 hour field demonstration of Johnson Matthey's L-CCRT Diesel Particulate Filter (DPF) on a NRE 3GS-21B genset switcher locomotive. Due to the fact that project funding came from two sources, SwRI tracked each funding source by separate SwRI Proposal Numbers and subsequently separate SwRI Project Numbers. SwRI Proposals 03-61484 and 03-61609, were collectively titled "Exhaust Emissions Testing Support of UPY2755 Locomotive L-CCRT DPF Field Demonstration."

The support of Union Pacific Railroad is especially appreciated through providing the test locomotive for evaluation, and for the transportation between Los Angeles, California and San Antonio, Texas.

TABLE OF CONTENTS

Page

EXECUTIVE SUMMARY ..... **i**

ACKNOWLEDGMENTS ..... **iii**

1.0 INTRODUCTION AND BACKGROUND **1**

2.0 TECHNICAL APPROACH **2**

2.1 Test Locomotive 2

2.2 Power Measurements 3

2.3 Fuel Consumption Measurements 3

2.4 Test Fuel 4

2.5 Exhaust Emissions Test Procedure 5

2.5.1 Gaseous Emissions Sampling *5*

2.5.2 Particulate Emissions Sampling *6*

3.0 TEST RESULTS **7**

3.1 Baseline FTP Data from UPY2737 7

3.2 UPY2755 Johnson Matthey L-CCRT DPF Installation on UPY2755 8

3.3 Test results at 0, 1,500 and 3,000 Hours 10

4.0 CONCLUSIONS **16**

APPENDICES **No. of Pages**

Appendix A: Baseline Engine Out Emissions Data from UPY2737 4
Appendix B: Zero-Hour Emissions Data from UPY2755 with the JM L-CCRT DPF Installed 3
Appendix C: 1500-Hour Emissions Data from UPY2755 with the JM L-CCRT DPF Installed 3
Appendix D: 3000-Hour Emissions Data from UPY2755 with the JM L-CCRT DPF Installed 4
Appendix E: 3000-Hour PM Sample Filter Analysis for SOF and Sulfate 1

LIST OF FIGURES

Figure **Page**

Figure 1. Test Locomotive UPY2755 2
Figure 2. UPY2755 With Manifold For Collecting Exhaust From All Three Stacks 5
Figure 3. Stock Muffler Visible After Removal of Roof Section 8
Figure 4. JM L-CCRT DPF Housing with Modified Roof Section 9
Figure 5. JM L-CCRT DPF Housings Installed 9
Figure 6. Switch Cycle Particulate Emissions Trend 13
Figure 7. Switch Cycle NOx Emissions Trend 14
Figure 8. Switch Cycle Brake Specific Fuel Consumption 15
Figure 9. NREC 3GS21B PM Emissions Summary 16

LIST OF TABLES

Table **Page**

Table 1. General Locomotive Data 3
Table 2. ULSD EPA Diesel Fuel Properties 4
Table 3. UPY2737 Baseline Test EPA Switch Cycle Results 7
Table 4. UPY2755 EPA Switch Cycle Results at zero hour 10
Table 5. UPY2755 EPA Switch Cycle Results at 1,500 Hour Test 11
Table 6. UPY2755 EPA Switch Cycle Results at 3,000 Hour Test 11
Table 7. UPY2755 EPA COMPOSITE 3,000 Hour test Switch Cycle Results (FTP #2, FTP #4, and FTP #5) 13

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.

On May 28, 2010, the City of Los Angeles Harbor Department and the Port of Long Beach jointly submitted a proposal to CARB for AB118 AQIP Advanced Technology Demonstration grant funding to demonstrate a Tier 4 locomotive DPM retrofit system on a 2,100 HP genset switcher locomotive. The project partners included Johnson Matthey, Inc., the technology provider, and Union Pacific Railroad, which used the retrofit system on a switching locomotive operating in the San Pedro Bay ports.

The project described in this report is follow-on to a 2010 ARB-funded project where initial proof-of-concept screening tests were performed on two candidate retrofit DPF systems.[1]

As part of a California AB118 project, Johnson Matthey's L-CCRT Diesel Particulate Filter (DPF) has been field demonstrated for 3,000 hours on a NRE 3GS-21B genset switcher locomotive, UPY2755. This final report covers the initial installation of the DPF, the initial "zero-hour" test results, 1,500 hour test results, and the 3,000 hour test results. At the end of this project, the Johnson Matthey's L-CCRT DPF system was left on UPY2755 and the locomotive was returned to operation in California.

---

[1] Hedrick, J.C., NREC Gen Set Locomotive DPF Assessment," SwRI Final Report 03.15322 to the California Air Resources Board," CARB Agreement 08-409, November 2010.

2.0 TECHNICAL APPROACH

Exhaust emissions testing for this project was performed by Southwest Research Institute 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, analytical procedures, and particulate measurement equipment and procedures.

2.1 Test Locomotive

Locomotive UPY2755 was used for this project and was provided by Union Pacific Railroad. UPY2755 was manufactured by NREC in July 2007 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 (1,570 kW).

UPY2755 is one of the 70 of this type of locomotives operating in California. These locomotives are certified as EPA Tier 2. UPY2755 is shown in Figure 1, and general locomotive information is shown in Table 1.

Figure 1. Test Locomotive UPY2755

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

UPY2755 Emissions Sticker

2.2 Power Measurements

The electric current produced by the three gen sets, normally sent to the traction motors in the locomotive, was routed to an external resistive load grid. The gross power of all three engines was determined using three, 3-phase watt meters (one per genset in the locomotive), and the manufacturer's published alternator efficiencies to calculate the engine gross or flywheel power. 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

This project utilized multiple batches of ultra-low sulfur diesel (ULSD). Fuel properties for all three batches of test fuel are provided in Table 2 and all test fuels met the fuel specifications called for in part of Title 40--Protection of Environment, Part 1065 - Engine Testing Procedures.

TABLE 2. ULSD EPA DIESEL FUEL PROPERTIES

ASTM Method	Test Property	Units	Zero Hour Test Fuel	1,500 Hour Test Fuel	3,000 Hour Test Fuel
D1319	Hydrocarbon Types by FIA				
	Aromatics	vol%	30.8	31.3	31.8
	Olefins	vol%	5.4	2.6	2.8
	Saturates	vol%	63.8	66.1	65.4
D240	Heat of Combustion				
	GROSS	BTU / lb	19584	19554	19,524
		MJ / kg	45.553	45.484	45.436
D240	Heat of Combustion				
	NET	BTU / lb	18375	18342	18,337
		MJ / kg	42.741	42.663	42.652
D4052	API Gravity	--	36	36.2	35.6
	Specific Gravity	--	0.8446	0.8439	0.8467
	Density at 15°C	grams / L	844.1	843.5	846.3
D445	Viscosity @ 40°C	cSt	2.425	2.416	2.444
D4629	Nitrogen Content	ppm	5.0	1.0	3.8
D4737	Cetane Index	(calculated)	45.9	46.8	46.3
D5186	Total Aromatics	mass %	28.8	29.2	30.0
	Mono Aromatics	mass %	23.5	22.9	23.4
	Polynuclear Aromatics	mass %	5.3	6.2	6.6
D5291	Elemental Analysis				
	Carbon Content	weight %	86.79	86.67	86.78
	Hydrogen Content	weight %	13.25	13.29	13.12
D5453	Sulfur Content	ppm	12.1	7.7	9
D613	Cetane Number	--	43.7	47.7	44.8
D93	Flash Point	Deg. F	159	150	150
		Deg. C	70	66	65
D86	Distillation				
	IBP	degF	361	345	344
	10%	degF	410	407	407
	50%	degF	489	492	496
	90%	degF	586	602	603
	FBP	degF	643	656	655
	Recovered	mL	98	97.2	97.6
	Residue	mL	1.3	1.5	1.5
	Loss	mL	0.7	1.3	1.9
EN14078	FAME Content	Volume %	<0.5	<0.5	<0.5

2.5 Exhaust Emissions Test Procedure

SwRI performed all 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, as shown in Figure 2. The gaseous and particulate sample probes were mounted in a section of manifold near the outlet of the manifold.

Figure 2. UPY2755 With Manifold For Collecting Exhaust From All Three Stacks

A heated sample line was used to transfer the raw exhaust sample from the probe mounted in the exhaust collection 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. The filters were mounted in a stainless steel filter holder connected to the sample probe. Particulate filters were conditioned and weighed before and after testing, over 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.

Due to the low levels of PM emissions emitted with the JM L-CCRT DPF System installed, the particulate sampling system components were cleaned and conditioned before testing UPY2755. 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 (600 seconds). PM results were then calculated without a tunnel blank correction, and with a tunnel blank correction.

3.0 TEST RESULTS

Johnson Matthey (JM) developed their L-CCRT DPF for this application under a separate project with SwRI, prior to the CARB funded tests. The ARB and JM co-funded project reported herein supported the L-CCRT DPF installation and the emissions tests on UPY2755 during the 3,000 demonstration project.

The results of this project are provided in the following sections:

- Baseline engine-out FTP data from UPY2737.
- Johnson Matthey L-CCRT DPF system Installation.
- Test results at Zero, 1,500 and 3,000 Hours of field operation with Johnson Matthey L-CCRT DPF system installed.

3.1 Baseline FTP Data from UPY2737

No engine-out baseline emission measurements were made on UPY2755. Baseline engine-out data were taken on UPY2737 as part of a previous CARB project, and this data was compared to the results from UPY2755 with the L-CCRT DPF installed. The triplicate engine-out baseline tests on UPY2737 used TxLED-ULSD diesel fuel, with an additional single FTP test performed using high-sulfur (2,814 ppm) EPA locomotive certification fuel. The baseline EPA Switch Cycle exhaust emissions for UPY2737 are summarized in Table 3. Detailed notch-by-notch results for each test are included in Appendix A. When operating 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 Switch Cycle NOx 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 diff.			**0.006**	**(0.00)**	**0.12**	**0.10**	**0.06**
ULSD avg vs. HSD, % diff			2%	-1%	10%	3%	53%

A baseline test on UPY2737 was also conducted using high-sulfur (2814 ppm S) EPA certification diesel fuel to check the emissions sensitivity to high sulfur fuel. The changes in emissions were within the range expected, with NOx increasing slightly and PM increased to 0.16 g/hp-hr.

3.2 UPY2755 Johnson Matthey L-CCRT DPF Installation on UPY2755

Photos taken during the installation of the JM L-CCRT DPF are shown in Figures 3, 4 and 5. The JM L-CCRT DPF housing was not designed to directly replace the NREC locomotive muffler / silencer, which is shown in Figure 3. The L-CCRT DPF housing, shown in Figure 4 protruded above the long hood roof section over the engine where the muffler / silencer originally mounted. The roof of the long hood was modified to accommodate the installation of the L-CCRT DPF. The interface between the long hood roof of the locomotive and the JM L-CCRT DPF housing was designed to keep rain out of the car body. While taller than the existing locomotive car body, the highest point on the JM L-CCRT DPF was lower than the highest point on the locomotive, and was below the AAR Plate L height limitation. Figure 5 shows the installed JM L-CCRT DPF on all three engines.

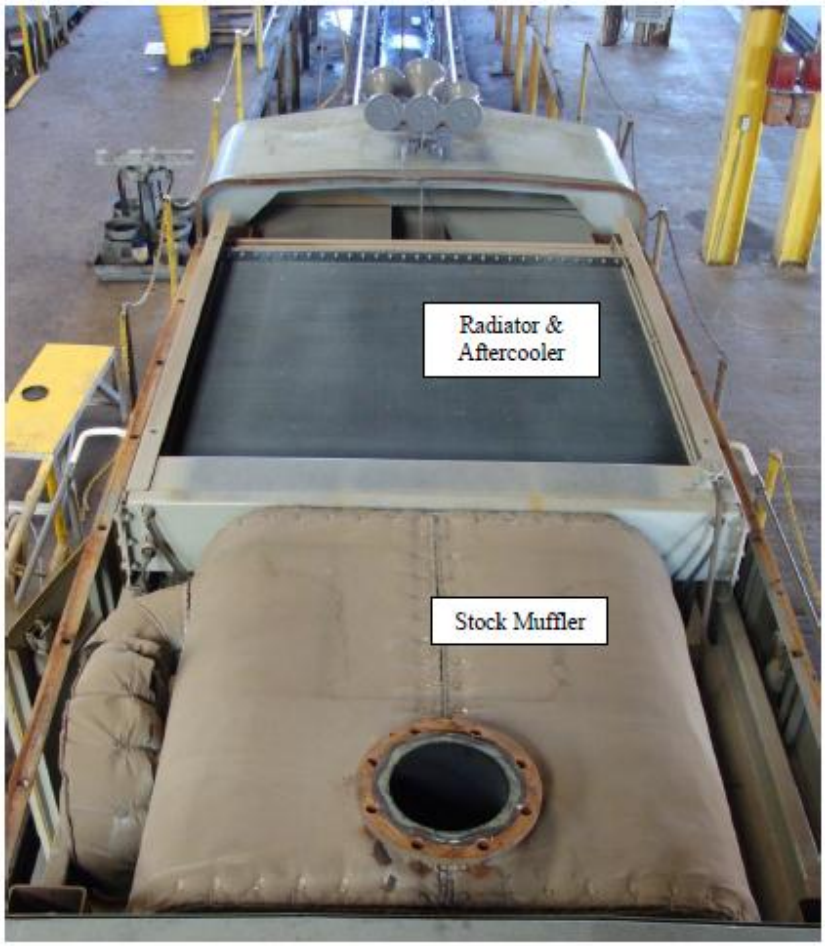


Figure 3. Stock Muffler Visible After Removal of Roof Section

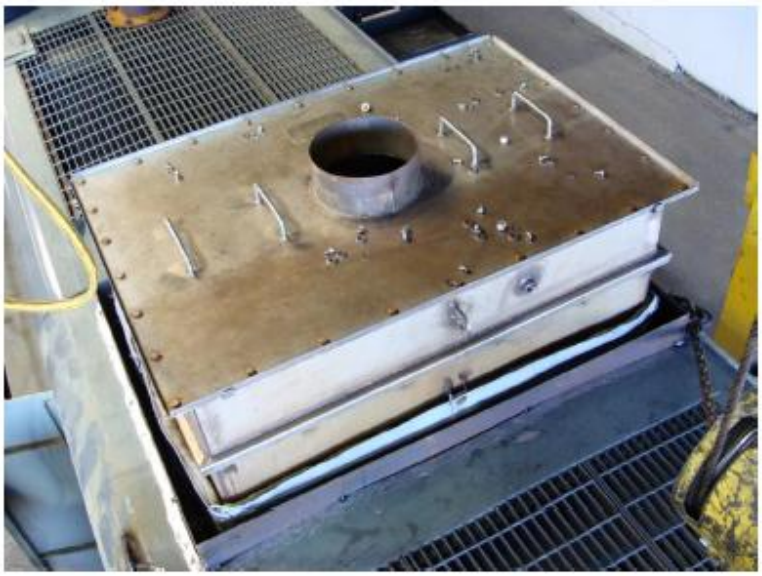


Figure 4. JM L-CCRT DPF Housing with Modified Roof Section

Figure 5. JM L-CCRT DPF Housings Installed

After the L-CCRT DPF installation process was completed, the L-CCRT DPF systems were degreened by operating each of the three GenSet engines for 20 hours at rated power. This degreening process allowed the DOC's and the diesel particulate filters to be conditioned before the start of the "zero hour" exhaust emissions testing. Additionally this operating time was used to assure that there were no exhaust leaks or thermal issues with the installation.

3.3 Test results at 0, 1,500 and 3,000 Hours

The "zero hour" test results, with the JM L-CCRT DPF installed, are shown in Table 4 and the full data set is provided in Appendix B. The JM L-CCRT DPF has a very active diesel oxidation catalyst (DOC) that was mounted on the front side of the DPF element. Compared to the engine-out baseline data from UPY2737, the L-CCRT DPF assembly reduced the HC emissions by 89 percent and essentially eliminated CO emissions. PM emissions were reduced by 97 percent from baseline levels, to 0.003 g/hp-hr. This PM level is 89 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.

TABLE 4. UPY2755 EPA SWITCH CYCLE RESULTS AT ZERO HOUR

Date	Fuel	Test	EPA Switch Cycle					TB Corr
			obs bsfc	HC	CO	NOx	PM	PM
			lb/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr
3-Jun-11	EPA Cert ULSD	FTP-A	0.402	0.02	0.00	2.7	0.004	0.002
3-Jun-11	EPA Cert ULSD	FTP-B	0.403	0.01	0.00	2.8	0.003	0.001
4-Jun-11	EPA Cert ULSD	FTP-C	0.423	0.01	0.00	2.6	0.003	0.002
Average JM-DPF			**0.409**	**0.01**	**0.00**	**2.7**	**0.003**	**0.002**
JM DPF c.o.v.			3%	13%	9%	2%	27%	55%
UPY2737 avg. vs. UPY2755, % diff			-2%	-89%	-100%	-8%	-97%	-99%
Percent below Tier 4 PM							-89%	

UPY2755 was returned to SwRI two additional times so that the locomotive emissions could be tested after 1,500 hours and 3,000 hours of operation in southern California. The 1,500 hour testing was conducted in early April 2012 and the final emissions test, at 3,000 hours of operation, was conducted in April 2013.

Just before the 1500-hour mark was reached, while still in revenue service in California, UPRR reported that the GEN 3 engine had mechanical problems. The decision was made to disable GEN3 and continue operating the locomotive to reach 1500 hours, and then move the locomotive to SwRI for assessment of GEN3 engine problems and repairs. After delivery of the locomotive to SwRI, the GEN 3 engine was repaired by the local Cummins dealer. The failure was a mechanical failure of one of the six individual cylinder heads, and was not thought to be due to the addition of the L-CCRT DPF system.

While the engine was being repaired, the GEN 3 L-CCRT DPF was removed from the locomotive car body so that the DPF elements could be inspected. The lid on the clean side of the L-CCRT DPF housing was removed and the DPF filter elements were visually inspected for signs of cracking or soot leaks in and around the filters (no elements were removed from the housing). The inspection suggested that there were no leaks inside the L-CCRT DPF housing. The lid was reinstalled on the L-CCRT DPF housing and it was reinstalled in the locomotive car body.

After the completion of the GEN3 engine repair and the reinstallation of the L-CCRT DPF housing, the locomotive was moved to the test track and instrumented. The engine in GEN 3 was then operated at rated power for approximately 6 hours to ensure that the engine was

capable of extended, full load, operation and that there were no coolant or exhaust leaks. After this was completed, the triplicate 1500-hour FTP emissions tests were performed.

The emissions results of the triplicate FTP emissions tests at 1,500 hours are summarized in Table 5, and the full data sets are provided in Appendix C. HC and CO emissions remain very low. NOx was essentially unchanged from the zero-hour tests. PM was 0.010 g/hp-hr, 68% below the UP-EPA Tier 4 PM limit. Although the 1500-hour PM results were 191 percent higher than the zero-hour results, they remained 68 percent below Tier 4 limits.

TABLE 5. UPY2755 EPA SWITCH CYCLE RESULTS AT 1,500 HOUR TEST

Date	Fuel	Test	EPA Switch Cycle					TB Corr
			obs bsfc	HC	CO	NOx	PM	PM
			lb/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr
24-Apr-12	EPA Cert ULSD	FTP-1	0.417	0.03	0.00	3.0	0.007	0.006
24-Apr-12	EPA Cert ULSD	FTP-2	0.408	0.01	0.00	2.8	0.011	0.008
24-Apr-12	EPA Cert ULSD	FTP-3	0.418	0.03	0.00	2.6	0.011	0.010
Average JM-1500-HR DPF			**0.414**	**0.02**	**0.00**	**2.8**	**0.010**	**0.008**
JM DPF c.o.v.			1%	58%	13%	7%	22%	24%
Percent below Tier 4 PM							-68%	

UPY2755 was returned to California in early May 2012 to complete the remaining 1500-hours of revenue service operation. The locomotive accumulated the remaining 1,500 hours of operation (3,000 hours total) by late February 2013 and was delivered to SwRI LTC in San Antonio Texas in April 2013.

Upon arrival in April 2013, UPY2755 was instrumented and installed on the test track to complete three FTP emissions tests and the results of the tests are shown in Table 6 and the full data set is provided in Appendix D. Note that an initial "FTP-1" test was run but was considered a practice run to ensure the locomotive would not ground fault through the FTP test. These 3,000 hour test results showed that the average PM was 0.026 g/hp-hr. The CO had a slight increase and the HC emissions were 0.01 g/hp-hr. Additionally the NOx emissions increased over the duration of the project, but remained well below the 3.37 g/hp-hr NOx emissions level that the locomotive was certified to meet.

TABLE 6. UPY2755 EPA SWITCH CYCLE RESULTS AT 3,000 HOUR TEST

Date	Fuel	Test	EPA Switch Cycle					TB Corr
			obs bsfc	HC	CO	NOx	PM	PM
			lb/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr
12-Apr-13	EPA Cert ULSD	FTP-2	0.425	0.01	0.01	2.8	0.022	0.022
13-Apr-13	EPA Cert ULSD	FTP-3	0.432	0.01	0.01	2.9	0.037	0.035
15-Apr-13	EPA Cert ULSD	FTP-4	0.434	0.01	0.01	2.8	0.019	0.017
Average JM-3000-HR DPF (FTP 2-4)			**0.430**	**0.01**	**0.01**	**2.8**	**0.026**	**0.025**
JM DPF c.o.v.			1%	14%	28%	2%	38%	40%
Percent below Tier 4 PM							-13%	

SwRI submitted the 3,000 hour test data (FTP-2, FTP-3, and FTP-4) to JM for review. Additionally, JM requested that specific PM sample filters be analyzed for Soluble Organic

Fraction (SOF) and sulfates and the results of these tests are provided in Appendix E. Based on the review of the test data, JM determined that the GEN 1 was not operating correctly and that this could be the cause of the high PM emissions measured during FTP-3.

All three engines were inspected by a representative from NREC. NREC found that GEN 1 had three bad or failed injectors, but was still able to achieve full power. With approval from UPRR and CARB, NREC installed a new set of six common rail fuel injectors in GEN 1 to correct the engine issue.

While the engines were inspected by NREC, JM staff inspected the three DPF's to determine if there were any issues with the elements or filter housings. The L-CCRT DPF housings were removed from the locomotive and the top lids of the L-CCRT DPF housings were removed and a thorough inspection was completed. During the inspection one of the v-band clamps in the GEN 3 L-CCRT DPF housing was found to be loose. This v-band clamp was used to hold one of the blanking plates in place that was directly over the exhaust inlet to the housing. Upon removal of the clamp, it was determined that the gasket between the housing flange and the blanking plate was also damaged. The gasket was replaced and the v-band clamp was reinstalled.

During the inspection, there was no soot found within the clean section of the L-CCRT, other than that found leaking from the GEN 3 L-CCRT gasket. The lack of soot on the clean side of two of the three L-CCRT's was an anecdotal observation of the PM reduction performance of the system.

All three L-CCRT DPF housing were then reinstalled on the locomotive. After the installation, each of the engines were operated for approximately six hours at rated power (Notch 3 which is rated power for one engine) to assure that there were no additional engine related issues and to make sure that the L-CCRT DPF systems showed no signs of exhaust leaks created during the L-CCRT reinstallation process. After confirming that there were no exhaust leaks, the locomotive was then re-instrumented and returned to the test track for one additional test (FTP-5).

During FTP-5, the locomotive experienced a ground fault error that stopped the testing after the Notch 6 test point was completed. JM had additional discussions with CARB about these results and the aborted FTP-5 emissions test results. After the meeting with CARB, JM instructed SwRI to:

- Substitute average Notch 7 and Notch 8 test data from FTP-2, FTP-3, and FTP-4 for the missing Notch 7 and Notch 8 data in FTP-5.
- Use the salvaged FTP-5 in place of FTP-3 in the 3,000 hour data set as GEN1 (with the suspect fuel injectors) was the lead engine for FTP-3.

The average results of FTP-2, FTP-4, and FTP-5 (replacing FTP-3) are shown in Table 7. The results of these tests showed that the EPA Switch Cycle PM emissions had increased to 0.021 g/hp-hr, or 30% below the Tier 4 PM level, and a PM reduction of 80 percent compared to

the UPY2737 baseline engine-out emissions. These results also shows that the NOx emissions remained below 3.0 g/hp-hr NOx level that this locomotive was certified to meet.

TABLE 7. UPY2755 EPA COMPOSITE 3,000 HOUR TEST SWITCH CYCLE RESULTS (FTP #2, FTP #4, AND FTP #5)

Date	Fuel	Test	EPA Switch Cycle					TB Corr
			obs bsfc	HC	CO	NOx	PM	PM
			lb/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr
12-Apr-13	EPA Cert ULSD	FTP-2	0.425	0.01	0.01	2.8	0.022	0.022
15-Apr-13	EPA Cert ULSD	FTP-4	0.434	0.01	0.01	2.8	0.019	0.017
6-Aug-13	EPA Cert ULSD	FTP-5[a]	0.421	0.02	0.00	3.0	0.022	0.020
Average JM-3000-HR DPF (FTP2,4,&5)			**0.427**	**0.01**	**0.01**	**2.9**	**0.021**	**0.019**
JM DPF c.o.v.			1%	17%	41%	0%	12%	20%
Percent Difference from Tier 4							-30%	

a - Note that FTP-5 is a composite of Idle through N6 with a separate FTP test which was terminated after Notch 6 due to a locomotive ground fault. A composite cycle result was calculated by including the average N7 and N8 data from FTP 2,3, and 4.

The PM emission trend over the duration of the project is shown in Figure 6. The percent difference between the PM emissions and the Tier 4 limit ranges from 89 percent below the Tier 4 limit at the zero hour test, and 30 percent below the Tier 4 limit for the 3,000 hour test.

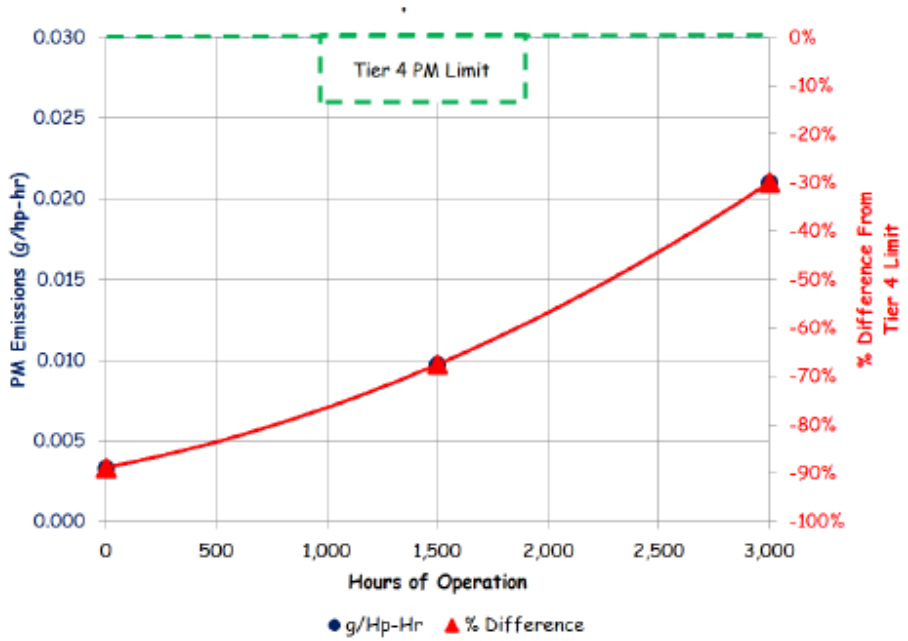


Figure 6. Switch Cycle Particulate Emissions Trend

There was a small change in Switch Cycle NOx emissions over the duration of the project. Figure 7 shows that the Switch cycle NOx emissions were below the NOx emissions

limit of 3.0 g/Hp-Hr, which is the level that the locomotive was certified, and about 65 percent below the Tier 2 emissions level of 8.1 g/hp-hr.

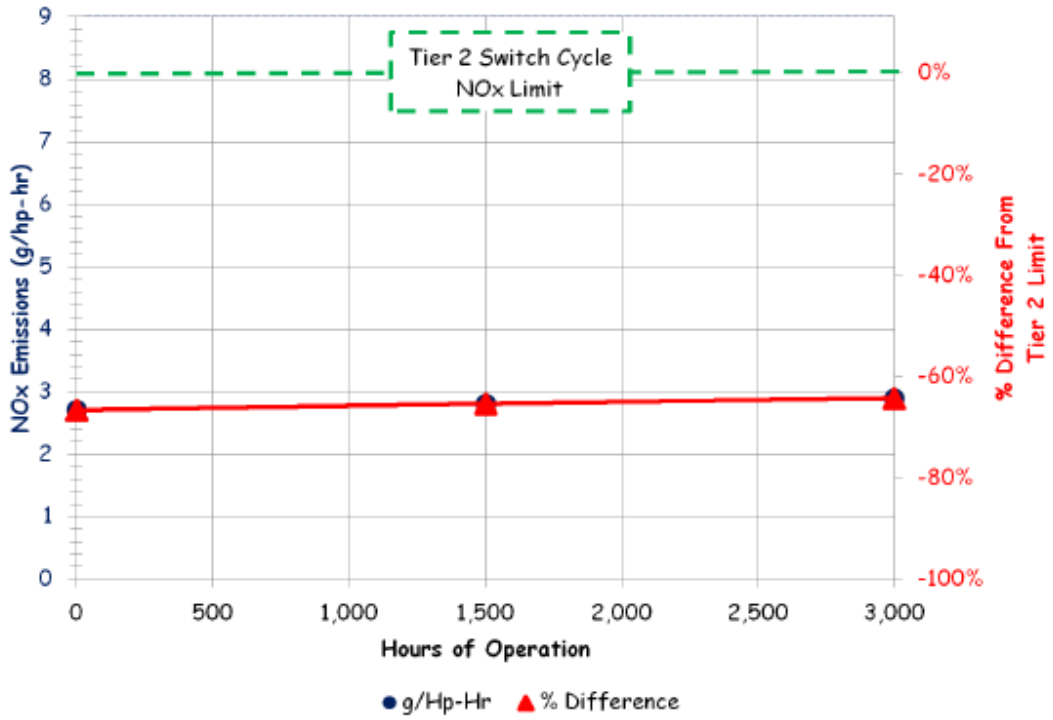


Figure 7. Switch Cycle NOx Emissions Trend

The HC and CO emissions remained very low throughout the duration of the demonstration and there was no trend in this data. The percent difference between the measured Switch Cycle HC emission and the Tier 4 limit was 85 to 90 percent below the limit.

Figure 8 shows the Switch Cycle brake specific fuel consumption (BSFC) for UPY2755 with the L-CCRT DPF installed, and the baseline test on UPY2737. Shown are 95 percent confidence intervals for the triplicate FTP tests, generated using the "confidence.t" function in Excel. Given the overlapping confidence intervals, the test data indicates that there was no statistically significant change in Switch cycle BSFC between the baseline UPY2737 without the L-CCRT and UPY2755 with the L-CCRT, nor was there a statistically significant change in Switch cycle BSFC for UPY2755 during the 3000-hour validation test.

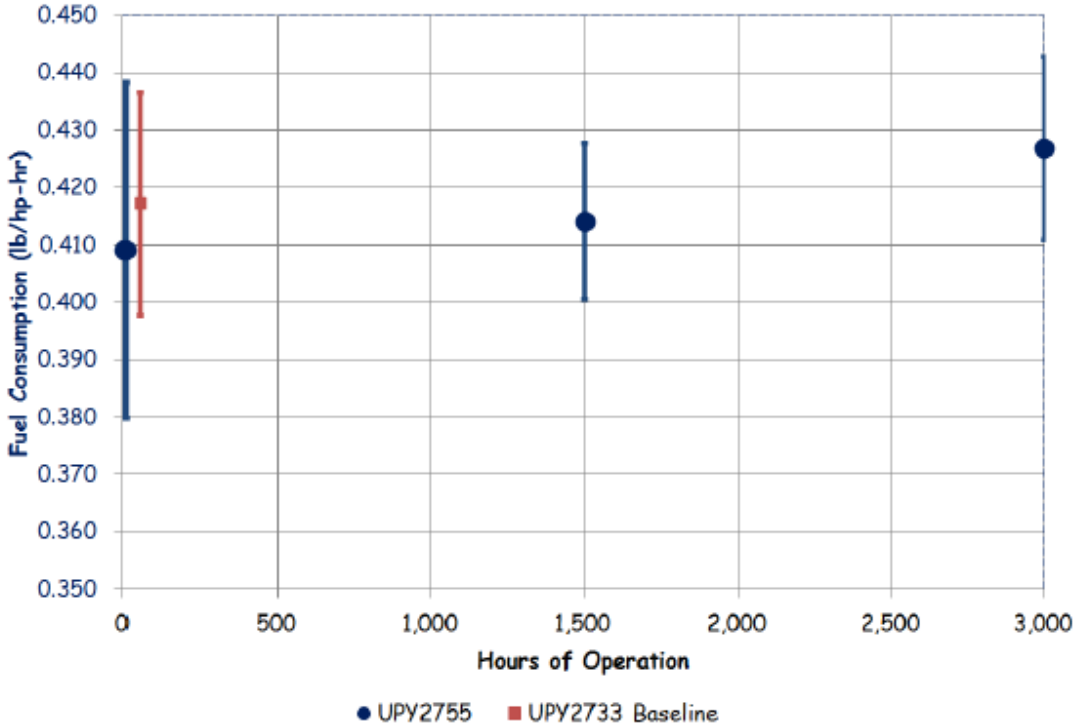


Figure 8. Switch Cycle Brake Specific Fuel Consumption

4.0 CONCLUSIONS

During the zero hour tests on UPY2755, the Johnson Matthey L-CCRT DPF systems installed offered significant reductions in FTP Switch Cycle HC and CO emissions when compared to the baseline locomotive, UPY2737. The addition of the L-CCRT DPF system did not increase NOx or cycle weighted fuel consumption.

Figure 9 shows the average US-EPA Switch Cycle PM emissions for the "zero-hour" tests were 0.003 g/hp-hr, which was 97 percent below the baseline engine-out PM emissions measured on UPY2737, and 89 percent below the US EPA Tier 4 PM limit of 0.03 g/hp-hr. The 1,500 hour test average Switch Cycle PM emissions were 0.010 g/hp-hr over the US-EPA Switch Cycle, or 68 percent below the Tier 4 PM limit of 0.03 g/hp-hr. During the final emissions test at 3,000 hours, the PM emissions were 0.021 g/hp-hr, or 30 percent below the Tier 4 PM emissions standard.

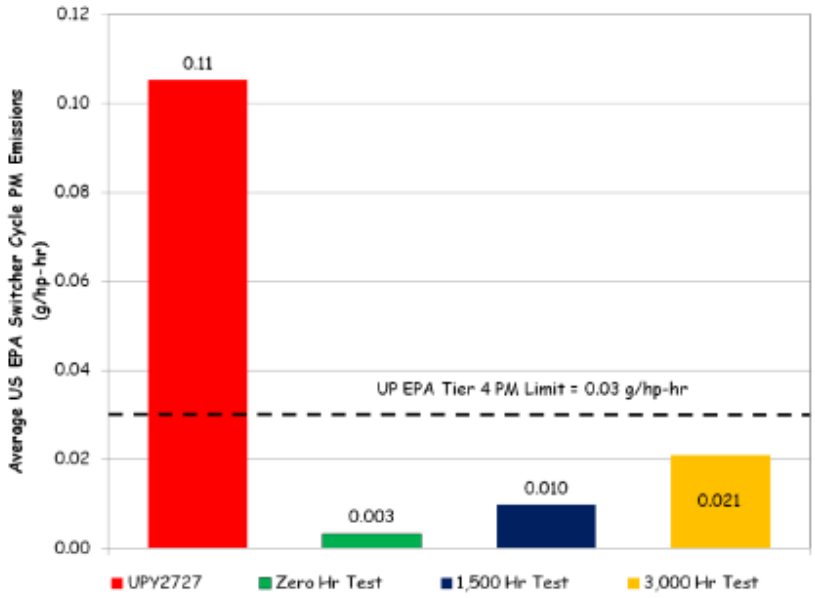


Figure 9. NREC 3GS21B PM Emissions Summary

APPENDIX A

Baseline Engine Out Emissions Data from UPY2737

COMPANY CONFIDENTIAL INFORMATION

Johnson Matthey Stationary Emissions Control LLC
900 Forge Avenue, Suite 100, Audubon, PA 19403-2305, TEL: 484-320-2114, FAX: 484-320-2152

Locomotive UPY2737 : CARB FTP #2 with TxLED-ULSD
Tested 25-JAN-2010 @ SwRI

COMPANY CONFIDENTIAL INFORMATION

Locomotive UPY2737 : CARB FTP #3 with TxLED-ULSD
Tested 25-JAN-2010 @ SwRI

COMPANY CONFIDENTIAL INFORMATION

Locomotive UPY2737 : CARB FTP #4 with High Sulfur (2719 ppm) Sulfur EPA Locomotive Certification diesel fuel (EM-3137M-F)
Tested 26-JAN-2010 @ SwRI

COMPANY CONFIDENTIAL INFORMATION

APPENDIX B

Zero Hour Emissions Data from UPY2755
with the JM L-CCRT DPF Installed

COMPANY CONFIDENTIAL INFORMATION

Johnson Matthey Stationary Emissions Control LLC
900 Forge Avenue, Suite 100, Audubon, PA 19403-2305, TEL: 484-320-2114, FAX: 484-320-2152

Locomotive UPY2755 : JM DPF Test B with ULSD EPA Cert diesel
Tested 03-JUN-2011 PM @ SwRI

COMPANY CONFIDENTIAL INFORMATION

Locomotive UPY2755 : JM DPF Test C with ULSD EPA Cert diesel
Tested 04-JUN-2011 AM @ SwRI

COMPANY CONFIDENTIAL INFORMATION

APPENDIX C

1,500 Hour Emissions Data from UPY2755
with the JM L-CCRT DPF Installed

COMPANY CONFIDENTIAL INFORMATION

Johnson Matthey Stationary Emissions Control LLC
900 Forge Avenue, Suite 100, Audubon, PA 19403-2305, TEL: 484-320-2114, FAX: 484-320-2152

Locomotive UPY2755 : JM 1500-HR DPF Test 2 with ULSD EPA Cert diesel
Tested 24-APR-2012 PM @ SwRI

COMPANY CONFIDENTIAL INFORMATION

COMPANY CONFIDENTIAL INFORMATION

APPENDIX D

3,000 Hour Emissions Data from UPY2755
with the JM L-CCRT DPF Installed

COMPANY CONFIDENTIAL INFORMATION

Johnson Matthey Stationary Emissions Control LLC
900 Forge Avenue, Suite 100, Audubon, PA 19403-2305, TEL: 484-320-2114, FAX: 484-320-2152

Locomotive UPY2755 : JM 3000-HR DPF Test 3 with ULSD EPA Cert diesel
Tested 13-APR-2013 @ SwRI

COMPANY CONFIDENTIAL INFORMATION

Locomotive UPY2755 : JM 3000-HR DPF Test 4 with ULSD EPA Cert diesel
Tested 15-APR-2013 @ SwRI

COMPANY CONFIDENTIAL INFORMATION

Locomotive UPY2755 : JM 3000-HR DPF Test 5 with ULSD EPA Cert diesel
Tested 06-AUG-2013 @ SwRI after GEN1 injector replacement and GEN3 DPF v-band clamp seal replacement

EP

EP

COMPANY CONFIDENTIAL INFORMATION

APPENDIX E

3,000 Hour PM Sample Filter Analysis for SOF and Sulfate

PROJECT NUMBER:	16478.01.001
PROJECT LEADER:	S.Fritz

TEST DATE	TEST NO.	FILTER NO.	CORR. SAMPLE PPM	ug SO4/ 90 FILTER	mg/SO4 90 FILTER	weight gain, mg	% SO4/ particulate	PM g/hp-hr
4/11/2013	FTP-1 Mode 5	56311	115.0	2300.6	2.301	4.7200	49%	0.143
4/12/2013	FTP-2 Mode 5	56320	16.61	332.3	0.332	0.5470	61%	0.015
4/13/2013	FTP-3 Mode 5	56366	53.5	1070.3	1.070	1.8810	57%	0.051
4/15/2013	FTP-4 Mode 5	56376	15.3	306.8	0.307	0.5470	56%	0.015
4/15/2013	FTP-2 Mode 8	56379	9.53	190.6	0.191	0.3720	51%	0.012

Project 03.16482.07.001	Soluble Organic Fraction Report	Filter 90mm
Project Leader : S. Fritz		
Test Dates :4/11-4/13/13		

Soluble Organic Fraction (SOF) Data (P-90)

Filter #	Test #	Filter Weight After Extraction (mg)	Filter Weight Before Extraction (mg)	Weight Loss (mg)	Weight Loss Corrected for the Blank (mg)	Particulate Weight before Extraction (mg)	Mass Fraction Extracted (mg)	% SOF	Corrected Blank Weight Loss After SOF Extraction (mg)	
56311	a5	272.3200	275.2870	2.9670	2.6842	4.7200	2.8790	93.6		
56320	a5	299.8640	300.3350	0.4710	0.1982	0.5470	0.3337	59.4		
56366	a5	279.6220	280.9550	1.3330	1.0652	1.8810	1.1474	92.4		
56369	a8	282.1360	282.5510	0.4150	0.1422	0.3020	0.1840	77.2		

APPENDIX F: Photos of UPY-2755 equipped with three JM L-CCRT™

Photos of UPY-2755 equipped with three JM L-CCRT™

Photos of UPY-2755 equipped with three JM L-CCRT™

Y2755
UPY
2755
UPY
2755
UPY
2755

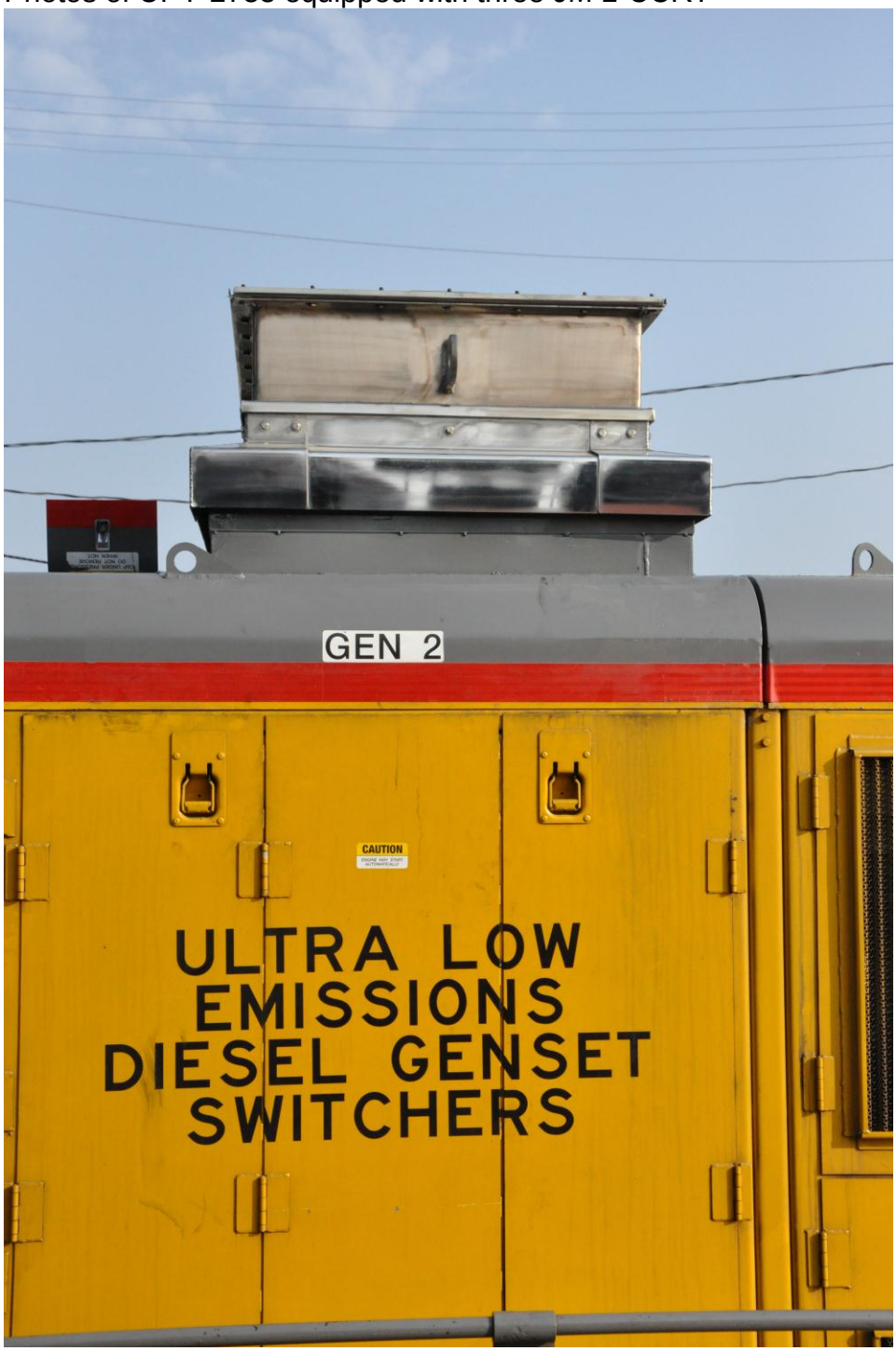
LDING
ERICA

Photos of UPY-2755 equipped with three JM L-CCRT™

Photos of UPY-2755 equipped with three JM L-CCRT™

GEN 1
BUILDING
AMERICA
UNION
PACIFIC

Photos of UPY-2755 equipped with three JM L-CCRT™



Photos of UPY-2755 equipped with three JM L-CCRT™

Photos of UPY-2755 equipped with three JM L-CCRT™

Photos of UPY-2755 equipped with three JM L-CCRT™

UPY
2755
UNION PACIFIC
UPY
2755
ENGINES OF CHANGE

APPENDIX G: SWRI-LTC Repair Report for Engine#3, 2012

GEN 3 ENGINE REPAIR - 2012

John Hedrick

Steve Fritz

Southwest Research Institute

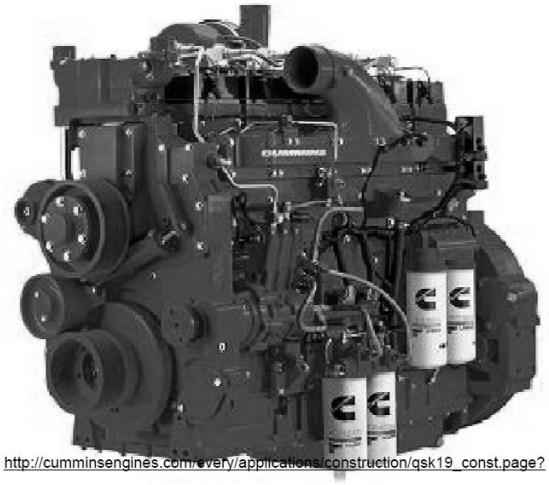
San Antonio, Texas

Locomotive

- UPY2755 = NREC Model 3GS-21B
  - Ultra Low Emissions Locomotive (ULEL).
  - Originally built 2007.
  - Modified to demonstrate JM DPF retrofit system.
- Modified to accept Johnson Matthey (JM) Diesel Particulate Filters (DPF) mounted above each engine.
- Locomotive operating in California as part of a technology demonstration.

Diesel Engine

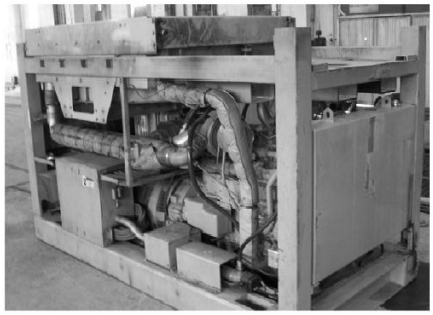
- Powered by 3, diesel engine driven, gen sets.
  - Cummins QSK19C
    - 19 liter
    - In-line 6 cylinder
    - Turbocharged
    - Air-to-air aftercooled
    - Common Rail fuel injection
  - Essentially US EPA Tier 3 non-road.
  - 522 kW each engine



http://cumminsengines.com/every/applications/construction/qsk19_const.page?

GEN 3 History

- GEN 3 originally failed May, 2011.
  - During rated power operation to de-greening JM DPF.
- Failure caused coolant to enter the oil sump.
- GEN 3 was replaced in June 2011 with used Pod provided by UP.
  - Unknown history of replacement POD.
- UPY2755 returned to revenue service in California to continue DPF durability testing



New GEN 3 Problems Reported

- Field reports of GEN 3 problems in Feb. 2012
  - GEN 3 Engine shutdown due to overheating.
    - Thought to be result of combustion gases entering cooling system.
  - Signs of water at exhaust system joints.
- UPY2755 approaching 1,500 DPF operating hours
  - UPRR and JM received OK from CARB to disable GEN 3 and continue hour accumulation using GEN 1 and GEN 2

UPY2755 Moved to SwRI – April 2012

- UPY2755 Moved to SwRI – April 2012
  - 1,500 hours of DPF-equipped operation
  - SwRI to assess GEN 3 and coordinate repairs with UPRR
- When delivered to SwRI:
  - Engine found to have very low (empty?) engine coolant level.
  - There were no signs of external water leaks.
  - Radiator fans appeared to work correctly.
  - GEN 3 engine oil level OK and not "milky" due to excessive water in the oil.

Initial GEN 3 Engine Inspection

- SwRI initial inspection of GEN 3:
  - Removed GEN 3 DPF.
  - Added water to cooling system.
  - Ran engine unloaded (with open exhaust pipe and at idle) with no issues noted.
  - Pressure checked the cooling system (hot) to look for leaks.
    - None found.

GEN 3 Engine Inspection

- Cummins Southern Plains (CSP) contracted to complete repair of engine.
  - CSP Invoice sent directly to UPRR.
- SwRI staff for parts review and assist.

- Initial step was to remove exhaust manifold and start engine.
  - Engine shot water out if exhaust ports – across shop!

GEN 3 Engine Inspection - Oil Analysis

- 4 oil samples taken.
  - New oil from storage tank on Gen 3
  - Gen 1 – Used
  - Gen 2 – Used
  - Gen 3 – Used
- Samples analyzed using ICP
  - ASTM D 5185

Oil Analysis

OilCode	UPY 2755	UPY 2755 GEN 1	UPY 2755 GEN 2	UPY 2755 GEN 3
	FRESH OIL 4/11/12	4/11/2012	4/11/2012	4/11/2012
Aluminum	<1	6	2	2
Antimony	<1	<1	<1	<1
Barium	<1	<1	<1	<1
Boron	27	10	16	38
Calcium	2468	3174	2994	2393
Chromium	<1	3	2	<1
Copper	<1	6	4	8
Iron	2	72	78	62
Lead	<1	10	7	6
Magnesium	11	16	12	108
Manganese	<1	<1	<1	<1
Molybdenum	1	4	4	31
Nickel	<1	<1	<1	1
Phosphorus	1054	1051	1005	1025
Silicon	3	19	6	9
Silver	<1	<1	<1	<1
Sodium	6	10	10	55
Tin	<1	3	2	2
Zinc	1236	1341	1274	1225
Potassium	5	6	5	194
Strontium	1	1	1	1
Vanadium	<1	<1	<1	<1
Titanium	<1	<1	<1	<1
Cadmium	<1	<1	<1	<1
All values are in parts per million				

- Gen 3 engine oil had high levels of:
  - Boron
  - Magnesium
  - Molybdenum
  - Sodium
  - Potassium
- Part of the coolant package.
- Changed GEN 3 oil & filters.

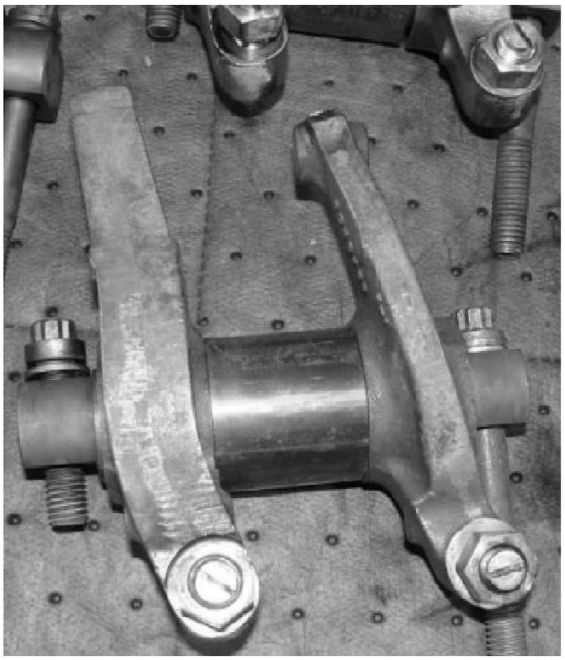
Parts Inspection – Water Pump & Thermostat

- SwRI removed water pump & checked impeller, driveshaft, etc.
  - Found it to be in good shape.
    - No "smoking gun" with the water pump.
    - Water pump bearing dragging a little – later replaced water pump
- Thermostats were removed and replaced.
  - Original thermostats were checked in hot water and were full open at ~ 190°F.

Parts Inspection – Rocker Arms & Pistons / Rod Length

- Rocker arms & push tubes inspected to assure no issues due to hydraulic lock.
  - Found minor surface rust on rocker arms.
  - Rocker arm bearing were found to be in good shape.
  - No damage to rocker arm or push tubes.
- Pistons checked at TDC to determine if rods were bent.
  - No issues found.

Parts Inspection – Surface Rust on Rocker Arms

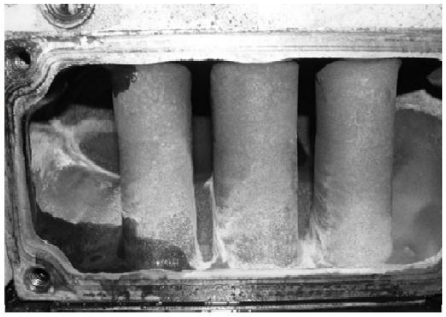


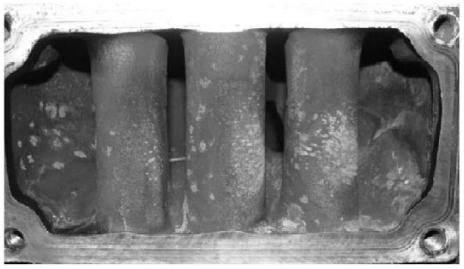
Parts Inspection – Misc Parts

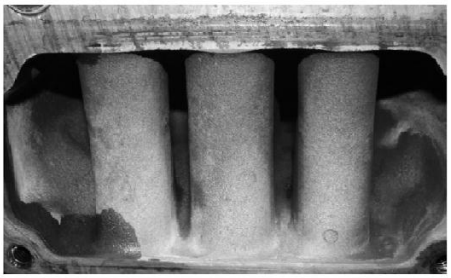
- Valve covers showed no signs of deposits.
- Thermostat housing was unremarkable with no signs of damage.
- Water jumper lines showed no signs of cracks or damage.
  - Inspected lines between:
    - Engine and radiator
    - Radiator and water pump
    - Water pump and block
    - Water filter housing and block
    - Engine oil cooler
- No signs of water leaks from radiator.

Parts Inspection – Cylinder Heads

- Removed intake manifold and found water stains in majority of cylinder ports.
- Signs of surface rust in most intake ports.







Parts Inspection – Cylinder Heads

- Close inspection of the cylinder heads showed a possible casting flaw in intake port could be initial cause of coolant leak.
  - Signs of water deposits downstream of flaw.
  - Only visible with inspection mirror.
    - Shown with red circle in photo.

Engine Assembly

- Cylinder heads replaced with Cummins UTEX.
- Thermostats replaced with new Cummins parts.
- Replaced water pump with Cummins UTEX.
- Filled GEN 3 cooling system with 50/50 mixture of water and Cummins-approved propylene glycol.

Added Instrumentation

- Installed 2 Thermocouples to measure the engine jacket water temperatures
  - Thermostat outlet (= radiator inlet)
  - Radiator outlet
  - After engine repair, both TC's showed reasonable operating temperatures while running engine at rated power.

GEN 3 DPF Inspection

- GEN 3 DPF inspected for damaged.
  - DPF housing removed from GEN 3
  - Lid removed exposing clean side of filters.
  - No leaks or DPF failure on the clean side.
  - Dirty side of the filters were inspected via the 8" inlet pipe of DPF housing.
    - No signs of coolant deposits or damage.

- No DPF filters were removed from the housing.

GEN 3 Engine Operation – Post Repair

- UPY2755 connected to external load grid, started, and GEN 3 operated at full load.
  - Open exhaust pipe (no DPF installed)
  - No overheating issues
  - No leaks (oil/coolant/boost/exhaust)
- Leak in the common rail fuel system was found.
  - Fuel from drip tube indicating fuel between double walled high-pressure lines
  - Potential fuel spill / fire risk.
  - Replacement high pressure fuel lines installed by CSP.
  - Repair completed by CSP and load tested by SwRI before unit was released to UPRR.

Engine Operation – Run-in

- GEN 3 DPF reinstalled.
- UPY2755 was moved to test track and reconnected to load grid.
- GEN 3 operated for 6 hours at rated power.
  - Notch 3
  - Additional instrumentation monitored and the engine cooling system operated well.
- Proceeded with planned FTP triplicate tests for JM DPF verification at 1500-hour mark

Conclusions

- UPY2755 GEN 3 engine appeared to have a cylinder head w/ casting flaw in intake port.
  - Caused coolant leak into the engine intake at low loads.
    - Also allowed coolant to enter the engine oil sump.
  - Allowed boost air into cooling system at high loads
- Low coolant levels caused engine to overheat.
  - Caused other heads to fail / crack.
- All cylinder heads replaced w/ Cummins UTEX heads April 2012.

Conclusions

- No other engine or cooling system issues were identified.
- After the engine repair, the GEN 3 engine operated for ~6 hours at rated power without engine overheating or other engine related issues.
- Engine failure did not appear damage DPF.
- Fuel leak identified on common rail injection system.
  - Repair of fuel system completed before release to UPRR.

APPENDIX H: 2600 Hour Repair Report for Engine#3, 1/16/2013

During the second 1500 durability period, an engine malfunction caused the temporary removal of the switch locomotive from service, at about 2600 hours of durability service, and an inspection of the L-CCRT filters ensued. It was found that during periodic maintenance of the switch locomotive, i.e. federally mandated 90 day regular maintenance, oil was overfilled in the oil sump, causing excess oil consumption to be ingested into the combustion system, and causing an accelerated L-CCRT Filter backpressure increase. The scheduled maintenance for UPY-2755 is shown in the table labeled UPY-2755 Maintenance History Summary, below. During the highlighted timeframe of 1/10-1/15/12, the overfilling of oil into the engine sump was carried out.

The primary indicator demonstrating a malfunction in the system was the rapid increase in backpressure, which was being monitored with the onboard data acquisition system. As shown in the figure below, the backpressure exceeded 40” w.c. (engines OEM maximum operating pressure) to a pressure of 47” w.c., in January 2013. Since the 3 systems operated well below the maximum threshold for the first 2600 hours, it was a surprise to see one system, gen #3, to exceed it within a very short period of time. Once this trend was found, the engine was removed from operation, and the inspection of the #3 generator system was requested. This effect was isolated to Genset #3, after inspection of the filters and catalyst elements; it was found that unburned hydrocarbons and an excess level of soot accumulation on the face of these elements were exhibited. Inspection of the L-CCRT filters of Genset #1 and 2 found normal conditions, as was indicated by the backpressure monitoring trend. However, as shown in the photographs below, the filters were saturated with the excess hydrocarbons from the increased oil consumption of the engine.

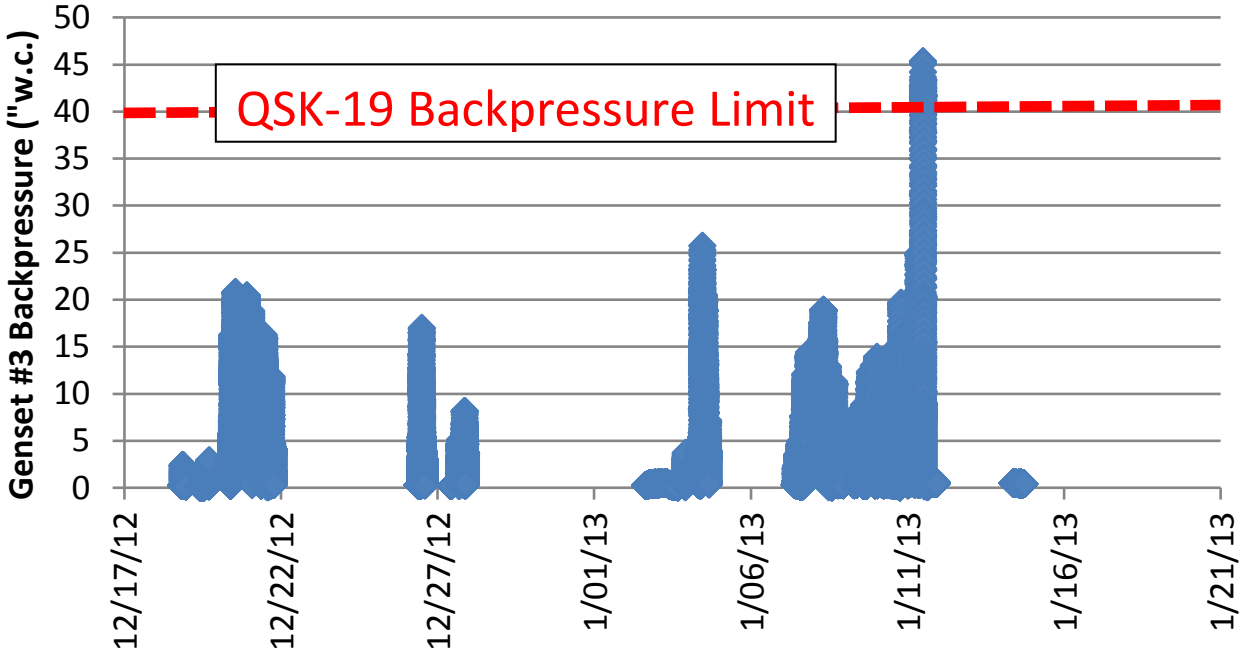


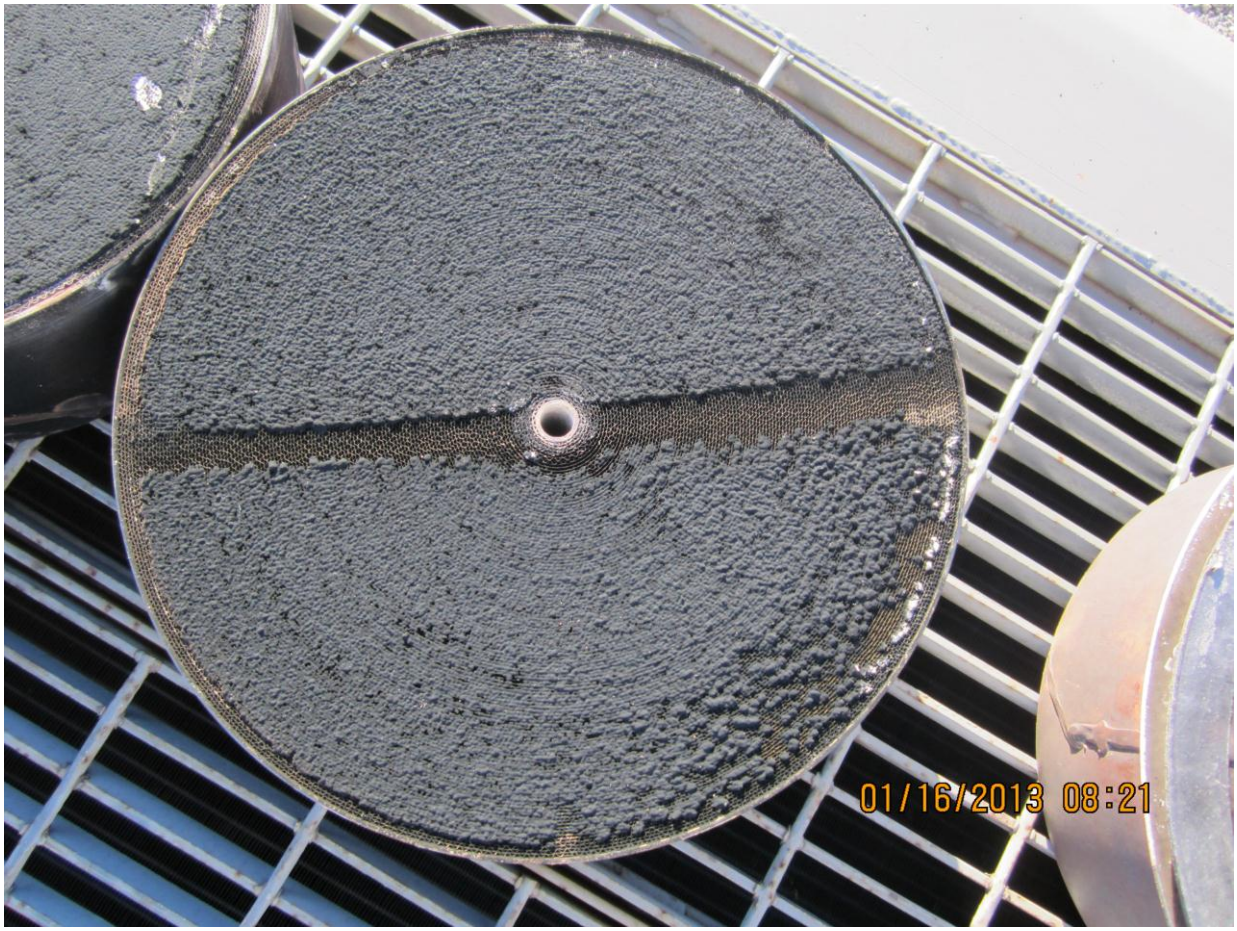
Figure 14: EGP of Genset #3 before the incident and during the January 2013 sudden EGP increase

Table 7: Malfunction Schedule for UPY-2755 during the 3000-Hour Durability Period

Incident	Date	Incident/Problem	Source of Problem	Description of Repair Measures
1	5/5/2011	During degreening of L-CCRT™'s on UPY-2755, engine #3 had a major engine malfunction during N-3 operation. The result of this engine malfunction was a total engine replacement. Coolant was injested into the exhasut stream, and passed through the L-CCRT on genset #3.	Inspection of the engine found that coolant had entered the oil system, possibly from some crack in the crankcase system. However, no root cause was determined during engine repairs.	Since the malfunction occurred before the beginning of the project, the engine #3 was removed and replaced with a completely new pod. This pod was a standalone replacement, provided by UPRR, and installed on UPY-2755 by SWRI. The L-CCRT was inspected and no changes were made.
2	2/20/2012	Engine #3 was disabled due to a malfunction that caused the engine cooling system to exceed its normal operating temperature	The root cause of the malfunction was observed to be a defect in the casting of the #5 cylinder head intake port of the engine.	During an inspection of the L-CCRT™ it was found that no significant impact was imparted to the system during the malfunction of the engine. Further, after the engine repairs were completed the Genset #3, with the L-CCRT™ installed, was run and monitored for back-pressure and temperature. Results of this preliminary test found that all performance parameters were within normal operation, and further validated the engine repairs and the normal operation of the DPF system.
3	1/16/2013	During this second period, an engine malfunction caused the temporary removal of the switch locomotive from service, at about 2600 hours of durability service, and an inspection of the L-CCRT filters ensued.	It was found that during periodic maintenance of the switch locomotive, i.e. federally mandated 90 day regular maintenance, oil was overfilled in the oil sump, causing excess oil consumption to be ingested into the combustion system, and causing an accelerated L-CCRT Filter backpressure increase. This effect was isolated to Genset #3, and is described in more detail in Appendix H of this report. After inspection of the filters and catalyst elements, it was found that unburned hydrocarbons and an excess level of soot accumulation on the face of these elements was exhibited.	It was agreed that the filters and catalyst elements could be cleaned via CARB approved cleaning methods. After the filters and catalyst elements were installed onto genset #3 and the engine was repaired, the switch unit was re-assembled and returned to revenue service.
4	8/15/2013	During the 3000 hour testing, it was found that the emissions coming from genset #1 were significantly hgiher than previously tested. As such, an evaluation of the 3 gensets was carried out to verify the operation of the locomotive. It was found that 3 of the 6 fuel injectors of genset #1 were not operational, creating a non-optimal engine operation. It was decided, after review with CARB, that the injectors (6) from the engine would be replaced, so that re-testing of the 3000-hour FTP test could be completed	Genset #1 was diagnosed by UPRR technician to be operating with only 3 functional fuel injectors; out of 6.	All 6 fuel injectors were replaced with new fuel injectors on genset #1. Also, the 3 L-CCRT's were reassembled onto UPY-2755, after a visual inspection was carried out. It was found that the L-CCRT on genset #3 had one of the gaskets on one of the filters decay. This was attribued to the interaction of the glycol in the exhaust stream during the malfunctions described in #1 and #2, in this table. The gasket was replaced and all other original components were reinstalled. The UPY-2755 was then retested under the 3000-hour FTP.

UPY 2755 - Maintenance History Summary

Dates	Description
7/5-7/8/11	Return to service after DPF installed; quarterly federal inspection, change fuel, air filters, clean out HVAC system, service air brake system, change out 2 traction motors, replace 2 pipes
8/26-8/27/11	Change out fuel filters account multiple loco stalls & fuel not reaching engine
10/4-10/6/11	Quarterly federal inspection; repair remote reporting comm system. Determined fuel system was clogged due to algae contamination in fuel trank.
11/25/11	Troubleshoot loco for repeat stall problem; normal company maintenance tasks
11/30-12/1/11	Bring in loco to flush out fuel system & replace all fuel filters
12/9/11	Complete fuel system repair & repair video camera
12/11/11	Change rectifier (on traction motor)
1/10-1/15/12	Quarterly federal inspection; change out fuel & air filters, repair various electrical system components (generator bushings)
1/27/12	Replace brake shoes
2/1/12	Repair ARC system (video camera)
2/3/12	Change out ditch/headlights
2/8/12	Engine surging reported - no defects found
2/23/12	Repair broken window
3/27/12	Quarterly federal inspection, routine maintenance (sand, coolant added)
5/11-5/16/12	Repair HVAC system, replace batteries, change lube oil,
5/31-6/1/12	Repair remote reporting system
7/11-7/15/12	Quarterly federal inspection, adjust journals/wheels, wash exterior & interior
9/9-9/11/12	Company maintenance, adjust handrails (safety equipment)
10/5/12	1 pod reported as dropping out
10/18-10/20/12	Quarterly federal inspection, repair flat spots on wheel
11/11/-11/12/12	Electric system malfunction - change out voltage regulator
11/24-11/25/12	Change filters, reapir manifold
11/28-11/29/12	Clean out overfilled oil; change heater/air conditioner
12/13-12/14/12	Routine company maintenance, change high voltage filters, change traction motor blower
1/8/13	Repair brake system
1/19-1/23/13	Quarterly federal inspection, repair flat spots on wheel



As shown in the photos above and below, the DOC's from Genset #3 were masked with unburned hydrocarbons and excess soot accumulation.

After meeting with the members of the AQIP project, it was agreed that the filters and catalyst elements could be cleaned via CARB approved cleaning methods. After the filters and catalyst elements were cleaned, and the engine was repaired, the switch unit was re-assembled and returned to revenue service. As shown in Figure “13: EGP at Notch-3 for zero-hour, 1500-hr and 3000-hr FTP tests, 95% C.I. error bars,” the performance of the L-CCRT™ returned to normal operation after the repairs and maintenance.