# CASE STUDIES OF THE USE OF EXHAUST EMISSION CONTROLS ON LOCOMOTIVES AND LARGE MARINE DIESEL ENGINES

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## 1.0 INTRODUCTION

Diesel engines provide important fuel economy and durability advantages for large heavy-duty trucks, buses, and nonroad engines. Although they are often the power plant of choice for heavy-duty applications, they have the disadvantage of emitting significant amounts of particulate matter (PM) and oxides of nitrogen (NOx), and lesser amounts of hydrocarbon (HC), carbon monoxide (CO), and toxic air pollutants.

Locomotive and marine diesel engines are significant contributors to air pollution in many cities, ports, and regions across the U.S. Due to relatively modest emission standards that are currently in place, current locomotive and marine diesel engines emit large amounts of NOx and PM and emissions of these air pollutants are expected to grow due to the anticipated future growth in the use of these engines. U.S. EPA estimates that by 2030, without new emission controls, locomotive and marine diesel engines will contribute about 27% of the national mobile source NOx and 45% of the national mobile source fine diesel particulate matter ($PM_{2.5}$) emissions. Therefore, the reduction of diesel emissions from locomotive and large marine engines has the potential to significantly improve air quality throughout the nation, as well as for those who live or work in or adjacent to ports and railyards.

Many of the diesel emission control technology options first developed for light-duty passenger cars, heavy-duty highway vehicles, and stationary engines (for application on both new vehicles and retrofits on existing vehicles) are now seeing limited application or are involved in feasibility studies on locomotive and large marine diesel engines. The experience with these diesel emission control technologies on highway vehicles provides an important experience and technology base for extending their application to locomotive, marine diesel, and other non-road diesel engines. These technologies include diesel oxidation catalysts (DOCs) and diesel particulate filters (DPFs) for controlling diesel PM emissions, and lean NOx catalysts and selective catalytic reduction (SCR) catalysts for reducing NOx emissions.

The extensive international experience base of SCR for controlling NOx emissions from stationary sources has been used over the past 15 years to develop NOx emission control solutions for mobile sources. Hundreds of SCR retrofit systems have been installed in the U.S. and Europe on large highway trucks since 1995. Operating experience exceeding 350,000 miles has been generated on some vehicles. SCR-equipped trucks using a urea-based reductant have been commercially available in Europe for nearly ten years with hundreds of thousands of units operating on the roads to comply with Euro 4 and Euro 5 heavy-duty engine emission regulations. SCR has been introduced on diesel passenger cars and heavy-duty trucks operating in the U.S. to comply with EPA's Tier 2 light-duty regulations and EPA's 2010 heavy-duty highway diesel emission regulations. These mobile source SCR systems can be designed to give significant reductions in NOx (75-90+%), as well as reductions in HC (80%) and PM (20-30%) emissions.

The operation of locomotive engines is quite different from on-road diesel trucks. Unlike trucks, long haul locomotives have powerful engines designed to operate at low speeds without the frequent transients experienced in on-road applications. In some ways, they more closely resemble stationary or marine engines in both displacement and operating cycle. SCR has been used to control NOx from stationary sources and large marine diesel engines for over 20 years.

An example of a large stationary retrofit of a diesel-powered generator incorporating both particulate control and SCR was presented at a conference in December 2005 (see www.nj.gov/dep/airworkgroups/docs/1chu.attachment5.pdf ). The engines in this demonstration were 2900 hp, 78 liter in size and were equipped with a catalyst-based, continuously regenerating particulate filter and SCR using a urea-based reductant. With more than 2000 hours of operation, these systems achieved reductions of greater than 90% PM, 94% NOx, 90% CO, and 75% HC, with less than 0.01 ppm ammonia slip. Many other stationary diesel engines have successfully achieved significant reductions in NOx emissions with properly designed SCR systems. Additional information on marine SCR experience is discussed in this report.

These, as well as other examples, clearly demonstrate that the NOx reduction technology originally developed for stationary engines has been successfully adapted to on-road vehicles and marine applications in Europe and suggest that emissions reductions from locomotive and marine engines would significantly benefit as well from the use of these same emission control technologies.

In an effort to address diesel air pollution from locomotives and marine diesel engines, EPA adopted more stringent emission standards for locomotives and marine CI engines less than 30 liters/cylinder in 2008. The regulation tightens emissions standards for existing locomotives and large marine diesel engines when they are remanufactured; sets near-term engine-out emissions standards (Tier 3 standards) for newly-built locomotives and marine diesel engines; and sets longer-term standards (Tier 4 standards) for newly-built locomotives and marine diesel engines that reflect the application of high-efficiency emission control technology (see www.epa.gov/otaq/marine.htm#2008final). On December 22, 2009, the U.S. EPA finalized its rulemaking for reducing emissions from large marine diesel engines that propel ocean-going vessels (Category 3 marine diesel engines, displacements at or above 30 liters/cylinder). The regulation harmonizes with the Tier 2 and Tier 3 emission standards that were added to the International Maritime Organization's (IMO) MARPOL Annex VI regulations. The EPA rule impacts vessels flagged or registered in the U.S. and includes a 2011 Tier 2 standard that relies on engine-based technologies to achieve a 15-25% reduction in NOx emissions relative to the existing EPA Tier 1 standards, and a 2016 Tier 3 standard that reduces NOx emissions by 80% relative to today's Tier 1 standards through the use of emission control technologies such as selective catalytic reduction. The Tier 3 standards include standards for hydrocarbons and carbon monoxide but do not include a standard for particulate matter. The Tier 3 engine emission standards are only required of ships operating within an approved Emissions Control Area (ECA). The U.S. EPA is requiring in this regulation that engine manufacturers measure and report PM emissions (see http://www.epa.gov/otaq/oceanvessels.htm).

On March 26, 2010, the IMO amended the MARPOL Annex VI designating the North American coasts as an ECA. The area of the North American ECA includes waters adjacent to the Pacific coast, the Atlantic/Gulf coast, and the eight main Hawaiian Islands. It extends up to 200 nautical miles from the coast of the United States, Canada, and the French territories. Implementation of the ECA means that ships entering the designated area would need to use complaint fuel for the duration of their voyage that is within that area, including time in port as well as voyages whose routes pass through the area without calling on a port. From the effective date in 2012, fuel used by all vessels operating in designated areas cannot exceed 1.0% sulfur

(10,000 ppm). (Large commercial ships currently use fuel with sulfur content as high as 45,000 ppm.) Beginning in 2015, fuel used by vessels operating in these areas cannot exceed 0.1% sulfur (1,000 ppm). Beginning in 2016, Tier 3 NOx standards (80% NOx reduction below Tier 1) become applicable (see http://www.epa.gov/otaq/oceanvessels.htm#north-american).

The 2015 fuel sulfur standard is expected to be met through fuel switching. In most cases ships already have the capability to store two or more fuels. However, to meet the 2015 fuel sulfur standard, some vessels may need to be modified for additional distillate fuel storage capacity. As an alternative to using lower sulfur fuel, ship operators may choose to equip their vessels with exhaust gas cleaning devices (e.g., "scrubbers"). EPA expects ships to meet the Tier 3 NOx standards through the use of high-efficiency NOx emission control technology (e.g., SCR).

As part of EPA's nonroad diesel rule (see: www.epa.gov/nonroad-diesel/2004fr.htm) that was adopted in May 2004, EPA has reduced the sulfur limit of diesel fuel used by locomotives and marine diesel engines to 15 ppm maximum starting in mid-2012. The use of ultra-low sulfur diesel fuel in locomotive and marine engines is an important enabler to allowing the use and maximizing the performance and durability of all available diesel emission control options for these engines.

Concurrent with efforts made by EPA, the California Air Resources Board (ARB) is also making strides in reducing diesel air pollution from locomotive and marine diesel engines. In December 2005, ARB adopted regulations for oceangoing auxiliary engines to reduce emissions from diesel PM, NOx, and SOx from vessels operating within 24 nautical miles of the California coastline. In 2011, ARB adopted amendments to the regulations "Fuel Sulfur and Other Operational Requirements for Ocean-Going Vessels within California Waters and 24 Nautical Miles of the California Baseline." The primary purpose of the amendments to the OGV Clean Fuel Regulation was to adjust the offshore regulatory boundary for the clean fuel zone in Southern California to lessen the potential for ocean-going vessels to interfere with operations at the U.S. Navy's Point Mugu Sea Range and to reestablish the anticipated emission reductions from the regulation. Additionally, the amendments help facilitate a successful transition to very low sulfur fuels by aligning implementation dates more closely with federal requirements. The amendments include extending the clean fuel zone further off shore and aligning it more closely in Southern California with the "Contiguous Zone," which is 24 nautical miles from the California shoreline. To facilitate a more successful transition to the 0.1% sulfur fuel, the Phase 2 implementation date was extended from January 1, 2012 to January 1, 2014.

In November 2007, ARB adopted its Commercial Harbor Craft regulation that requires engines on all new vessels and all engine replacements to be the cleanest available marine engines. This ARB harbor craft regulation also requires all new vessels and all engine replacements to be the cleanest available marine engines and requires Tier 1 or earlier auxiliary and propulsion engines on in-use ferries, excursion vessels, tugboats and towboats to meet EPA Tier 2 or 3 standards starting in 2009. In May 2009, ARB proposed amendments to these regulations to include in-use engine requirements for crew and supply vessels.

The case studies discussed in this paper focus on those projects that have been completed, or are in progress, that utilize emission control technology on locomotive and marine engines. Many of the projects highlight the feasibility of installing verified on-road retrofit technologies on locomotive and marine engines and relate some of the lessons learned that may assist others in planning additional locomotive and marine engine projects. The limited range of experience with retrofits on locomotive and marine engines summarized in this report also serves to point out the need for expanding the range of verified retrofit technology options for nonroad diesel applications in general, and locomotive and marine engines in particular. This paper focuses on technology-based strategies and, where available, provides information on the specific type of technology installed on the types of locomotive and marine engines, and the emission reductions that were achieved or are expected. For more detailed descriptions of available diesel exhaust emission control technologies that can be retrofit on existing on-road and nonroad diesel engines, please see MECA's companion white paper, *Retrofitting Emission Controls On Diesel-Powered Vehicles* (available on the MECA website at: www.meca.org or the MECA diesel retrofit website at: www.dieselretrofit.org).

## 2.0 LOCOMOTIVE CASE STUDIES

### *2.1 Locomotive Field Demonstration of Tier 4 PM Emission Control*

As part of ARB funded AB 118 project, sponsored by the Bay Area Air Quality Management District, GT Exhaust's passive diesel particulate filter system was field demonstrated for almost 2000 hours on a NRE 3GS-21B genset switcher locomotive, BNSF1284. Southwest Research Institute (SwRI) performed all of the testing and data collection.

The locomotive used for this project was BNSF1284, a 2100 horsepower NREC model 3GS21B, originally manufactured in April 2008. This switcher locomotive uses three diesel-engine driven generator sets to provide the power needed to drive the traction motors. The GT DPF retrofit system uses catalyzed DPF elements with passive regeneration capability. Initial testing showed that the DPFs reduced the PM emissions to 0.012 g/hp-hr or 61% below the locomotive Tier 4 limits. This phase of the project was to demonstrate the performance of the DPFs while BNSF1284 was in revenue service for 1500 hours (approximately 6 months).

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

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

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

The reprogramming of the RCL did not reduce the transient nature of the engines, although it did reduce the number of times they were started and stopped. While observing the operation, it was noted that the back pressure remained at acceptable levels. However, it was still not ideal operating conditions for a passive DPF system for the following reasons: exhaust temperatures at idle are only around 400F which is not hot enough for the passive regeneration to occur; passive DPFs typically require 15 to 20 minutes at or above the regeneration temperature in order to burn off the soot and prevent the back pressure from getting too high.

GT was forced to end the project prematurely when a manufacturing facility closure in the DPF supply chain meant they would no longer be a commercially available product. The 1500 hour midpoint test became the final test and was completed in February 2013, after 1990 hours of operation.

The final test in February 2013 showed that PM was reduced to 0.027 g/hp-hr or 10% below Tier 4 PM requirement limits. The DPFs were removed and returned to GT for inspection and the original mufflers were reinstalled on the locomotive. BNSF1284 returned to revenue service in Richmond, CA.

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

- In this demonstration with RCL, the 2$^{nd}$ and 3$^{rd}$ engines are called on infrequently and only for short periods of power. The rest of the time, they are operated at idle or off, neither condition having enough temperature to allow the soot to be regenerated in the DPF. Because of this, soot will likely build up in the DPF causing the back pressure to increase to levels above the engine manufacturer's specifications. As a result, there will need to be a method of adding heat to the exhaust into the DPF to activate regeneration at idle conditions.
- Even with an external heat source, if a site plans to operate a multi-engine switcher as an RCL with DPFs, it will be necessary to validate that the RCL logic does not turn on and off the non-lead engines excessively. If it does, the logic should be modified.
- The GT Exhaust housing for the DPFs was designed to be compact and replace the existing mufflers with very minimal modifications to the locomotive. The housing fit completely under the roof of the locomotive. From the test results and final inspection, it

is concluded that the basic design concept, with small improvements, will be able to maintain the PM below Tier 4 levels.

More information on this is available at: http://www.arb.ca.gov/railyard/docs/final_report_gt_exhaust_june_12_2013.pdf.

### *2.2 Progress Rail LoNOx Locomotive with DOC and SCR: 12 Month Field Demonstration and Emissions Testing*

Progress Rail, a Caterpillar company, unveiled their new 3005 horsepower intermediate line-haul PR30C-LoNOx locomotive equipped with SCR and DOC aftertreatment. The model PR30C-LoNOx locomotive was designed to achieve EPA Tier 4 line-haul locomotive NOx level that will be required for locomotives in the U.S. starting in 2015. The 3005 horsepower PR30C, six-axle locomotive is an EMD SD40-2 chassis originally manufactured in the 1970's, but repowered with a Tier 2 Caterpillar 3516-HC diesel engine. When the engine is equipped with a Caterpillar developed advanced aftertreatment system that includes SCR technology, as well as DOC technology, the unit is designated PR30C-LoNOx.

The Progress Rail provided Union Pacific Railroad Company (UPRR) with five such locomotives for a one-year demonstration. ARB provided funding for the testing and evaluation of one of these LoNOx locomotives, road number PRLX3004, to investigate the feasibility of combining an advanced engine repower with an aftertreatment system on a medium horsepower freight line-haul locomotive. ARB funded emissions testing and remote monitoring for one of the locomotives during the evaluation period. Locomotive road number PRLX3004 was selected for the ARB funded testing and remote monitoring.

Phase 1 of the ARB funded program was conducted at the Southwest Research Institute (SwRI) Locomotive Technology Center, and included engine-out baseline emissions testing, aftertreatment installation, commissioning and aftertreatment degreening, 0-hour aftertreatment emissions testing, and data logging equipment installation. Phase 2 of the program consisted of monitoring and reporting in-service operation of the LoNOx locomotive PRLX3004 during a 12-month demonstration while it worked in the UPRR system, as well as performing additional emissions tests at the mid-point and end-point of the demonstration.

Triplicate emission tests were run to establish emissions for the engine-out baseline configuration of PRLX3004. Without the aftertreatment, the locomotive produced emission levels within Tier 2 EPA locomotive limits. The aftertreatment system was installed and 40 hours of rated power operation were used to degreen the aftertreatment system. This degreened condition was identified as the 0-hour point for the LoNOx configuration. Triplicate tests at the 0-hour point with degreened aftertreatment indicated a reduction in NOx of 80% over the line-haul cycle, and 59% over the switcher cycle, as compared to the baseline values. During this test program, ammonia slip volume concentration at the exhaust stack ranged from zero to 5 ppm.

The aftertreatment provided a total HC reduction from baseline of 93% over the line-haul cycle and 94% over the switcher cycle, and a CO reduction of 72% over the line-haul cycle and

81% over the switcher cycle. The PM reduction from baseline at the 0-hour testing was 43% over the line-haul cycle and 64% over the switcher cycle. Emission test results for the 0-hour PR30C-LoNOx configuration achieved Tier 4 line-haul NOx, CO, HC, and smoke emission levels, as well as Tier 3 PM levels. With completion of 0-hour testing of PRLX3004 in the PR30C-LONOx configuration, the locomotive was released to begin Phase 2.

Phase 2 of the ARB funded program started in December 2009 when the locomotive was released from SwRI to UPRR for revenue service. Throughout the field demonstration, SwRI provided weekly updates of in-use operation and performance data of locomotive PRLX3004 in the PR30C-LoNOx configuration. The locomotive was worked back to San Antonio for emissions testing in March 2010 after accumulating approximately 1,500 hours of operation, and again in November after accumulating approximately 3,000 hours of operation. For the 1,500- and 3,000-hour test points, emission results were similar to those of the 0-hour point. HC, CO, and NOx remained below Tier 4 limits and PM remained below Tier 3 limits. CO emissions were slightly lower for the 1,500-hour and 3,000-hour points compared to the 0-hour point, and the HC cycle composite values increased slightly from the 0-hour point. Test results indicated a small decrease in PM emissions at the 1,500-hour point, and again at the 3,000-hour point.

The overall diesel exhaust fluid (DEF) consumption increased slightly at each test point, and at the 3,000-hour point, reached a maximum of 4.8% volume of the fuel consumption over the line-haul locomotive duty cycle, and 3.2% volume of the fuel consumption over the switcher cycle. The upward trend in DEF consumption was accompanied with a downward trend in locomotive intake air humidity levels during testing, and was likely a result of increased engine-out NOx flow.

After 0-hour testing was completed for PRLX3004, the engine hour-meter reading was recorded as the starting point for the demonstration and a fresh clock began for the 3,000 hour field demonstration. PRLX3004 was placed outside the SwRI gate on November 4, 2009 to be picked up by UPRR and placed into revenue service. The locomotive was kept close to the San Antonio route while system operations were verified to be in good working order. The first service route PRLX3004 worked on in California was between West Colton and the Port of Los Angeles. PRLX3004 was placed in a California bound intermodal train and left San Antonio on January 18, 2010 and arrived in the Los Angeles basin on January 20 having already accumulated 986 hours of engine operation for the field demonstration.

After accumulating a total of 1,498 hours of engine operation for the field demonstration, PRLX3004 began to work back to San Antonio on March 20, 2010 for scheduled emissions testing. The locomotive arrived at SwRI on March 28 having completed 1,575 hours of engine operation in the field demonstration. At the conclusion of the 1,500-hour testing and inspection, PRLX3004 worked back to California and continued service on the West Colton/Long Beach until May 16.

On May 16, 2010, PRLX3004 changed service route assignments and began to operate between West Colton and El Centro. This is a 164 mile trip from the Los Angeles basin to a desert town near the California/Mexico border. PRLX3004 left West Colton on November 3 to begin the trip back to SwRI for the final set of emission tests, thus completing the El Centro service assignment. PRLX3004 was assigned to the El Centro service for a total of 171 days and accumulated an additional 1,167 hours of operation. The locomotive utilization improved slightly for the El Centro service as compared to the Long Beach service. Idling was reduced from 78% of the total engine operation while servicing Long Beach, to 65% for the El Centro service.

PRLX3004 arrived at SwRI on November 12, 2010 completing the demonstration with a total of 3,082 hours of operation. Engine idling and dynamic braking accounted for 80% of the total demonstration hours. The power producing modes contributed 611 hours to the total demonstration hours, making up 20% of the total duty cycle. The total elapsed time from the start of the demonstration on November 4, 2009, to the end of November 12, 2010, was 8,952 hours. The engine was off 66% of the total elapsed time, and provided power 7% of the time.

The estimated total MW-hour accumulated by PRLX3004 over the demonstration was 572 engine-brake MW-hours. When estimated using the net traction power instead of engine-brake power, the demonstration total was 484 MW-hours. Fuel consumption rates were measured by SwRI.

**Table 1: Summary of SwRI Emission Test Results for Progress Rail PR30C Locomotive PRL3004 in Baseline and LoNOx Configurations**

| | **Locomotive Line-Haul Cycle Composite Emissions** | | | | **Locomotive Switcher Cycle Composite Emissions** | | | |
|---|---|---|---|---|---|---|---|---|
| | **HC** | **CO** | **Corr. NOx** | **PM** | **HC** | **CO** | **Corr. NOx** | **PM** |
| **Test Description** | g/hp-hr | g/hp-hr | g/hp-hr | g/hp-hr | g/hp-hr | g/hp-hr | g/hp-hr | g/hp-hr |
| Tier 2 Limits | 0.30 | 1.5 | 5.5 | 0.20 | 0.60 | 2.4 | 8.1 | 0.24 |
| Tier 3 Limits | 0.30 | 1.5 | 5.5 | 0.10 | 0.60 | 2.4 | 5.0 | 0.10 |
| Tier 4 Limits | 0.14 | 1.5 | 1.3 | 0.03 | NA | NA | NA | NA |
| Baseline Ave. | 0.26 | 0.7 | 4.8 | 0.09 | 0.45 | 1.1 | 5.2 | 0.16 |
| 0-Hr Ave. | 0.02 | 0.2 | 0.9 | 0.05 | 0.03 | 0.2 | 2.2 | 0.06 |
| 1,500-Hr Ave. | 0.02 | 0.2 | 0.9 | 0.05 | 0.03 | 0.1 | 2.2 | 0.05 |
| 3,000-Hr Ave. | 0.02 | 0.1 | 0.9 | 0.04 | 0.03 | 0.1 | 2.1 | 0.04 |

Emissions test results from PRLX3004 show that the PR30C-LoxNOx locomotive achieved Tier 4 line-haul NOx, CO, HC and smoke emission levels, as well as Tier 3 PM levels (see Table 1 above). When tested in the baseline configuration, which is without the aftertreatment, the locomotive produced emission levels within Tier 2 EPA locomotive limits. At the 0-hour test point the aftertreatment provided a NOx reduction of 80% over the line-haul cycle, and 59% over the switcher cycle, as compared to the engine-out baseline values. The aftertreatment system (SCR and DOC) provided a total HC reduction from baseline of 93% over the line-haul and 94% over the switcher cycle. With the aftertreatment system, a PM reduction of 43% over the line-haul cycle, and 64% over the switcher cycle, as compared to baseline values, was measured.

No fuel penalty was detected for the aftertreatment, and the maximum diesel exhaust fluid consumption was 4.8% of fuel consumption by volume over the line-haul duty cycle, and 3.2% of the fuel consumption by volume over the switcher cycle.

The results from the 1,500-hour and 3,000-hour emission test points were similar to the 0-hour point. Cycle composite HC, CO, and NOx remained below Tier 4 limits, and PM remained below Tier 3 limits. CO emissions were slightly lower at the 1,500-hour and 3,000-hour test points, as compared to the 0-hour point. PM emissions were lower at the 1,500-hour and 3,000-hour points as compared to the 0-hour point. These results suggest there were no significant degradation in aftertreatment performance during the field demonstration, which included a total of 3,082 hours of engine operation and generated an estimated 572 MW-hour of power over the period of approximately one year.

More information on this project is available at: http://www.arb.ca.gov/railyard/docs/prlx3004_final-report_public-domain_05_20_2011.pdf.

### *2.3 EMD Tier 4 PM Aftertreatment Upgrade on a Line Haul Locomotive*

The goal of the project was to upgrade an experimental Tier 2, 3200 bhp, 2-cycle, line-haul locomotive with EGR using an aftermarket device consisting of multiple DOCs and DPFs. This aftertreatment upgrade is possible of the internal carbody modifications to allow space to apply the large aftertreatment system to the top of the engine. The main goal of this project was to provide an experimental locomotive that achieved an 80% PM reduction from Tier 2 levels.

This Advanced Technology Demonstration Project had the following goals:

- Demonstrate the durability of aftertreatment engine retrofit devices providing significant emission reduction benefits of PM
- Evaluate the performance of aftertreatment technologies installed on a medium horsepower Tier 2 locomotive
- Achieve EPA Tier 4 PM levels

The base platform for this project was an EMD SD60M locomotive that was repowered with an EMD 710ECO engine, which is EPA-certified and manufactured by Electro Motive Diesel (EMD). This project used a prototype Tier 2 12-710 engine to provide 25% increase in carbody space for application of the EGR system along with a larger cooling system. Diesel oxidation catalysts and diesel particulate filters were installed in series, integrated with the experimental EMD 710ECO, twelve-cylinder, 3200 bhp, two-cycle engine. The experimental engine had been designed for the EGR system and included a new turbocharger with sufficient boost to accommodate the DOC/DPF. The DPF was a catalyzed passive filter. EMD is committed to commercializing this advanced aftertreatment technology after the demonstration phase proves the aftertreatment delivers acceptable performance, durability, serviceability, and reliability.

Repowering the SD60M locomotive started with the removal of the existing 16-cylinder EPA Tier 0 diesel engine and replacing it with the smaller 12-cylinder EMD 710ECO Tier 2 engine. By reducing the size of the engine by 25%, space was created for the installation of an experimental EGR system.

Emissions data for the SD59MX with the EMD 710ECO Tier 2 repower engine alone are consistent with EPA Tier 2 requirements. See below Table 2 for baseline emissions data.

**Table 2: Baseline Emissions Data**

| | CO (g/bhp-hr) | $CO_2$ (g/bhp-hr) | NOx (g/bhp-hr) | HC (g/bhp-hr) | PM (g/bhp-hr) |
|---|---|---|---|---|---|
| **Test Data** | 0.210 | 525.1 | 5.285 | 0.149 | 0.122 |
| **Tier 2 Standard** | 1.5 | NA | 5.5 | 0.30 | 0.20 |

After application of EMD experimental EGR technologies for NOx reduction, prototype turbocharger and aftertreatment device consisting of DOC/DPF, the results in Table 3 below were obtained:

**Table 3: Emissions Data with EGR+DOC/DPF**

| | CO (g/bhp-hr) | $CO_2$ (g/bhp-hr) | NOx (g/bhp-hr) | HC (g/bhp-hr) | $CH_4$ (g/bhp-hr) | PM (g/bhp-hr) |
|---|---|---|---|---|---|---|
| **Test Data** | 0.052 | 538.4 | 3.387 | 0.015 | 0.003 | 0.011 |
| **Tier 4 Standard** | 1.5 | NA | 1.3 | 0.14 | NA | 0.03 |

Actual PM emissions were reduced by 95% over the Tier 2 levels and well below the Tier 4 line-haul standard of 0.03 g/hp-hr. HC emissions were reduced by 90%. Both baseline and final emissions test used ultra-low sulfur diesel (ULSD) fuel meeting EPA's specification with no correction for the sulfur content being made to the final data.

EMD notes that the DOC/DPF prototype will be one step in developing an emissions reduction technology with high potential for future commercialization. This project will assist EMD with the development of the 710 engine family for Tier 4 PM emissions and will allow the necessary reliability data to be gathered supporting new 4,000+bhp line haul locomotives.

There are approximately 21,000 active EMD locomotives currently operating in North America. About 4,000 of these engines move through California. This PM reduction technology is intended to help attain the EPA Tier 4 standards for line haul locomotives. According to the final report, it is most likely to be too expensive, too big or too heavy for practical implementation as retrofit technology to reduce PM on existing line haul locomotives. Also, the current configuration is marginally maintainable. It remains to be seen if this technology can be commercialized beyond application to new locomotives.

A copy of the final report is available at: http://www.arb.ca.gov/railyard/docs/final_report_emd_tier_4_pm_aftertreatment_upgrade_83112_final_v1.pdf.

### *2.4 Demonstration of Compact SCR in Passenger Locomotive*

In 2007, Engine, Fuel, and Emissions Engineering, Inc. (EF&EE) received a contract from the South Coast Air Quality Management District (AQMD) to demonstrate selective catalytic reduction (SCR) on a passenger locomotive. The objective of this project was to demonstrate that NOx and PM emissions from existing locomotives could be reduced substantially by retrofitting them with EF&EE's Compact SCR technology. This was the first application of SCR technology to a North American locomotive.

The contract for this work was partly funded by AQMD funds and partly by EPA grant. Additional grant funding for the project was subsequently received from the Texas Environmental Research Consortium. Additional in-kind support was received from the Southern California Regional Rail Authority; ARB, in the form of emissions testing carried out by Southwest Research Institute; and from EF&EE.

The demonstration was hosted by the Southern California Regional Rail Authority, which is the joint-powers agency responsible for the Metrolink rail commuter service in the Los Angeles region. The vehicle for the demonstration was SCAX 865, and EMD model F59PH passenger locomotive equipped with an EMD 12-710G diesel engine rated at 3000 tractive horsepower. This engine was built before federal emissions standards were adopted for locomotive engines, and has not been remanufactured to meet the Tier 0 standard.

EF&EE developed and constructed the first prototype SCR catalyst assembly, comprising 24 round catalyst monoliths mounted in two groups of 12, one on each side of a central plenum. The Compact SCR system uses 32% urea solution (DEF) as the reductant. The SCR catalyst assembly was fitted into the space previously occupied by the locomotive silencer with a urea metering system, on-board urea storage tank, and a PLC control and datalogging system. The catalyst assembly is shock-mounted to protect the ceramic catalyst elements from shock and vibration, and is connected to the turbocharger exhaust outlet by a flexible coupling.

The SCAX 865 returned to daily commuter service on February 19, 2009. Baseline emission tests were conducted in August 2008 and in February 2009 prior to installation of the SCR system. Additional emission tests were conducted in February and May 2009.

During the emission testing conducted in May 2009, it was observed that most of the SCR catalyst modules had suffered cracks. The cracking pattern indicated that it was likely due to angular vibration of the catalyst modules. An attempt was made to stiffen the existing structure to limit the magnitude of those vibrations, but this was ineffective. The SCR catalyst assembly was removed from the locomotive pending redesign.

EF&EE staff redesigned the SCR catalyst assembly to provide lateral support for both the upstream and downstream ends of the catalyst modules (previously, only the upstream ends had been supported). The new structure was tested first by reinstalling the catalyst assembly with 21 of the old catalyst modules along with three new ones. After six weeks in locomotive service, no further catalyst cracking had occurred. At that point, the catalyst assembly was removed, and all of the cracked modules were replaced with new ones.

The locomotive returned to service with the modified SCR system on July 13, 2010. Since the system returned to operation, the SCR catalyst assembly has been removed once to correct an assembly error that allowed some of the bolts to vibrate loose. As of October 12, 2010 it had accumulated more than 1108 engine operating hours.

This project has demonstrated the feasibility of retrofitting Compact SCR to a Tier 0 locomotive engine. Baseline emission tests were conducted on the locomotive before the SCR catalyst was installed, and additional tests were conducted before returning it to service. Emission measurements conducted by EF&EE showed net reduction of 71% and 61% in NOx and PM respectively, over the EPA line-haul cycle; and of 61% and 57% over the EPA switch cycle. The NOx emissions were 2.6 g/bhp-hr in the line-haul cycle and 4.6 g/bhp-hr in the switch cycle. This is well below EPA Tier 3 levels. PM emissions were 0.12 g/bhp-hr in both cycles, slightly exceeding the Tier 3 PM standard of 0.10 g/bhp-hr.

**Table 4: Baseline and SCR System Emissions Data**

| | **Emissions (g/bhp-hr)** | | | |
|---|---|---|---|---|
| | **PM** | **CO** | **NOx** | **HC** |
| **Line Haul Cycle** | | | | |
| **Baseline** | 0.290 | 0.74 | 9.00 | 0.06 |
| **Compact SCR** | 0.115 | 0.18 | 2.64 | <0 |
| **% Reduction** | 61% | 76% | 71% | 100% |
| **Switch Cycle** | | | | |
| **Baseline** | 0.273 | 0.79 | 11.80 | 0.06 |
| **Compact SCR** | 0.116 | 0.13 | 4.60 | <0 |
| **% Reduction** | 57% | 84% | 61% | 100% |

Emission testing conducted immediately beforehand showed NOx and PM reductions of 51% and 41% in the switch cycle. The lower efficiency in these tests was ascribed to urea leaks resulting from missing bolts. NOx emissions could be further reduced by improving the mixing between the urea solution and the exhaust. Complementary measures to reduce engine idle time would reduce the emissions produced when the exhaust temperature is too low for SCR.

The project was initially estimated to reduce NOx emissions by 24 tons per year and PM by 0.5 tons per year. This was based on estimated control efficiencies of 80% for NOx and 50% for PM, and an erroneously high estimate of baseline emissions. Actual emission reductions are estimated at 8.9 tons per year of NOx and 0.2 tons per year of PM. The main reason for the difference is that annual baseline NOx and PM emission were lower than originally estimated: about 15 and 0.4 tons per year, respectively.

The average NOx control efficiency achieved was also somewhat lower than expected, at 71%. Overall NOx control efficiencies greater than 90% are typical in marine compact SCR marine installations, but it was expected that the efficiency would be less for locomotives, due to the large fraction of the operating time spent at idle. The exhaust temperature at idle is too low for the Compact SCR system to operate. The NOx control efficiency at high load was also lower than expected, averaging about 80% rather than 95%+ typical in marine installations. This shortfall was due to the limited mixing length available in the locomotive exhaust flow path before the catalyst. This made it impossible to achieve a homogeneous mixture between the urea reductant and the exhaust.

The ongoing durability demonstration of the project was continued through July 2011. EF&EE developed a new design to eliminate the remaining weaknesses identified in the current design. The new design retains the improved catalyst support proven in this project, but rearranges the catalyst modules into a configuration that is thinner from top to bottom and thicker from front to back. This arrangement increases the available mixing length, and is also compatible with the use of diesel PM downstream.

More information on this project is available at: http://files.harc.edu/Sites/TERC/NTRD/Projects/N011FinalReport.pdf.

### *2.5 Demonstration of a Liquefied Natural Gas Fueled Switcher Locomotive at Pacific Harbor Line, Inc.*

In order to reduce air pollution from rail operations within and surrounding the ports of Long Beach and Los Angeles, Pacific Harbor Lines, Inc. (PHL) entered into an operating agreement with the ports to deploy lower-emitting technologies and fuels within the PHL fleet of switcher locomotives. PHL is required to lease or acquire one switcher locomotive fueled by LNG to demonstrate the technology's suitability and emissions reduction characteristics. In May 2009, PHL initiated a nine-month demonstration of an liquefied natural gas (LNG)-fueled switcher locomotive leased from Burlington Northern Santa Fe Railway (BNSF) at the Port of Los Angeles' West Basin Container Terminal (WBCT). This 1200 hp LNG locomotive (BNSF 1203) was the primary switcher locomotive used at WBCT during the duration of the demonstration project.

The original objective of the demonstration was for PHL to document operational parameters for the LNG locomotive (e.g., fuel consumption, reliability), and make comparisons to PHL's existing fleet of older, similarly sized diesel-electric switcher locomotives. PHL was unable to execute the test plan as originally written. By the time the LNG locomotive was ready to be tested, PHL had replaced its entire fleet of older 1200 hp switcher locomotives with larger, newer technology switchers meeting or exceeding EPA's Tier 2 emission levels.

A modified test plan was implemented with consultation with the ports. The revised plan called for the test LNG switcher to be operationally compared to PHL's older 1200 hp diesel-electric switchers, using recent historical data. This provided the most "apples to apples" comparison because the two types of switcher locomotives are similar in size and capabilities. Additionally, emissions comparisons were made under the revised plan of the LNG switcher versus both types of diesel-electric locomotives.

Using the modified demonstration test plan as approved by the ports, the LNG switcher was operated by PHL for a period of 36 weeks. Beginning in early August 2006, PHL began working with ports to develop a test plan that would capture the necessary data to implement a meaningful LNG locomotive demonstration. The resulting test plan outlined a one-year test consisting of two phases. In the first phase, the LNG locomotive was to be operated for six months in tandem with a diesel switcher from the PHL fleet. Typically, two 1200 hp diesel switcher ("smurfs") were used to provide intermodal service. The size and power of the LNG locomotive made it a comparable replacement for one of the diesel smurf units. In the second phase of the testing, the LNG locomotive was to operate in "solo" mode providing car switcher service at the Yang Ming yard.

In 2007, PHL began phasing out its 1200 hp diesel switcher smurfs, replacing them with the newer Tier 2 switcher locomotives. As a result, the tandem operation portion of the original test plan was not conducted. Instead, the LNG locomotive was operated in "solo" mode for the entirety of the demonstration period, and the performance of the LNG locomotive has been compared to historical data of a smurf in the same solo mode of operation.

Due to budget and time constraints, emissions tests were not performed on the LNG or diesel locomotive for this project. As a surrogate, existing emissions data for the LNG and diesel locomotives were used to derive estimated emissions levels in duty cycle similar to PHL's typical switcher operations. Emissions factors from PHL's diesel fleet are taken from the Port of Long Beach emissions inventory for 2008; these data are used in this report for the baseline diesel emissions rates. LNG emissions rates are taken from a report prepared by BNSF Railway, Union Pacific Railroad, and others as presented to the ARB. The emissions data for the LNG locomotive were collected prior to EPA establishing a switcher duty cycle, however, they represent the only known emissions rates for the Caterpillar 3516G in a switcher locomotive application. Based on the similarity of the duty cycles between the diesel and LNG locomotives, it is reasonable to assume that emissions from the locomotives would be comparable to the ratios of the emissions rates given in Table X below. Specifically, it is anticipated that NOx would be reduced by 92% and PM by 76% from the LNG locomotive compared to the Tier 0 baseline diesel locomotive. Compared to PHL's current fleet of tier 2 diesel locomotives, it is anticipated that NOx emissions would be reduced by 81% and PM emissions by 57%.

**Table 5: Emissions Rates for LNG, Baseline Diesel, and Tier 2 Locomotives (g/bhp-hr)**

| **Locomotive Type** | **Fuel** | **NOx** | **CO** | **THC** | **PM** |
|---|---|---|---|---|---|
| MK1200 LNG | LNG | 1.4 | 2.2 | 3.3 | 0.09 |
| Baseline Diesel | Diesel | 17.6 | 1.83 | 0.87 | 0.38 |
| Tier 2 Diesel | Diesel | 7.30 | 1.83 | 0.52 | 0.21 |

The nature of LNG makes the fueling process and fuel consumption measurements significantly different from those involving diesel fuel. LNG must be kept at cryogenic temperatures to maintain its liquid state. Heat leakage into the fuel tanks causes the fuel to slowly boil off over time. As a result, there is a difference in the amount of fuel that is ultimately available to the engine for combustion and locomotive power. There is also the potential to vent fuel during the refueling process, resulting in LNG fuel that is recorded as used without ever making it into the locomotive's onboard fuel tank. This venting is ideally minimized using a "vapor collapse", which was utilized when the LNG switcher was refueled. While some benefit was achieved using the vapor collapse process, PHL still noted significant difficulties each time the LNG locomotive was refueled, throughout the demonstration. Consequently, significant volumes of LNG were vented/lost during refueling events.

**Table 6: LNG Fuel Consumption**

| LNG Purchased | LNG Consumed (Diesel Equivalent Gallons) | LNG Vented (Diesel Equivalent Gallons) | Fuel Consumption Ratio |
|---|---|---|---|
| 19,673 (vendor provided) | 17,340 (calculated) | 2,330 (calculated) | 88.2% |

The baseline diesel fleet of smurfs at PHL historically exhibited exceptionally high reliability, considering the average age of the fleet. PHL found the LNG switcher locomotive's overall reliability to be average, but less than its diesel smurf fleet. Of the 11 mechanical issues reported by PHL for the LNG switcher locomotive, fiver were related to LNG-specific components, i.e., those that do not exist on diesel-electric locomotives. Three of the five issues were related to the fueling process for the locomotive. PHL consistently cited fueling as the most difficult aspect of operating the LNG locomotive. In particular, the mobile LNG refueler truck was typically unable to completely fill the locomotive's LNG fuel tanks, due to pressure build-up in the tanks. The resulting partial fill had two effect: first, the resulting reduction in on-board energy diminished the locomotive's operating time capacity. Second, the inside of the vacuum-insulated LNG tanks were not being cooled as much as they would be during a complete fill. This resulted in progressively higher tank temperatures at the beginning of each fuel operation. The LNG locomotive was only able to be fueled to about one-third of the rated fuel capacity.

Based on data and observations provided by PHL, the following conclusions are made of the demonstration project:

- Overall, the LNG locomotive performed "adequately to well" in car switching service. However, the logistics and mechanical issues associated with fueling negatively impacted the locomotive's service capability.
- Mechanical issues with fueling compounded already difficult fueling logistics associated with the local fire department's requirements.
- Based on the service events for the LNG locomotive in comparison with the diesel fleet, PHL feels the reliability of the LNG locomotive is average but less reliable than the diesel locomotives. This is primarily due to the addition of system components required for spark-ignition engine; and fueling problems.
- Compared to the existing diesel switcher fleet, the LNG locomotive required similar level of maintenance and facilities support. However, the level of effort required to support fueling and address fuel-related mechanical issues was exceptionally high.
- Emissions from the LNG locomotive were estimated to be 92% lower in NOx, and 76% lower in PM, compared to the baseline (uncontrolled) diesel locomotives that PHL has already phased out. Compared to PHL's new Tier 2 locomotives, emissions from the LNG locomotive were estimated to be 81% lower in NOx and 57% lower in PM. However, it is important to recognize that these three types of switcher locomotives differ in age and emissions control technology, among other factors. This makes it difficult to isolate the emissions reduction contributions of using cleaner-burning LNG fuel in the test locomotive.
- The average fuel consumption for the test locomotive was 72 diesel-equivalent gallons per day. A comparable diesel switcher tested by PHL under a different program consumed about 65 diesel gallons per day. It appears that the newer engine technology of

the LNG locomotive roughly offset two inherent inefficiencies of dedicated LNG engines with respect to fuel consumption, which are: the lower thermal efficiency of spark ignition compared to compression ignition; and fueling and boil off losses associated with LNG.

- Despite its apparent higher rate of fuel consumption, the LNG locomotive cost approximately 23% less to fuel on an energy-equivalent basis, due to the lower price paid by PHL per British thermal unit (Btu) of LNG fuel compared to diesel fuel.

A copy of the final report on this demonstration project is available at: http://www.cleanairactionplan.org/civica/filebank/blobdload.asp?BlobID=2462.

## 3.0 LARGE MARINE ENGINE CASE STUDIES

### *3.1 Emissions from a Harbor Craft Vessel Using Retrofit Emission Control Technologies*

The U.S. Navy partnered with ARB and the Maritime Administration (MARAD) to test two diesel engine emission control technologies on a MARAD self-propelled barge crane. Two emission control technologies were selected for retrofit application to one of the two propulsion Detroit Diesel 12V-71 marine diesel engines on the barge crane. The Clean Cam Technology System (CCTS) combines turbo charging of the original naturally-aspirated engine along with in-cylinder changes to effect internal exhaust gas recirculation (EGR) and thereby reduce PM and NOx emissions. The Rypos active-regeneration DPF traps and burns off the PM in the exhaust gases.

ARB expects that once implemented, emissions of PM and NOx would be reduced by 40-50% by 2015, and 60-70% by 2025, compared to 2004 levels., The new measure for commercial harbor craft does not include recreational or ocean-going vessels.

ARB estimates that there are approximately 4,200 harbor craft vessels and 8,300 harbor craft engines currently in use in California (with each vessel typically having more than one engine). While these represent only 15% of the vessels (25% of the engines), they generate about 50% of the emissions. Additionally, most of their emissions are generated within the harbor or close to shore and have the greatest impact on adjacent communities. About 40% of these vessels are in the Bay Area, while 30% service the ports of Los Angeles and Long Beach. The remainder are scattered throughout the State.

The goal of this project was to compare the emissions of the two retrofit control technologies with emissions from an identical engine without retrofits. Testing was conducted shortly after installation of the retrofit control technologies, and then again after a nine-month operating period. The specific plan measured emissions from the starboard (baseline) engine and the controlled port engine on a working harbor craft. Testing followed the ISO 8178 (E3) cycle as close as practical for in-use engines installed in a vessel. Testing occurred on open water in and around Suisun Bay, CA.

The Naval Reserve Fleet at Suisun Bay maintains a variety of diesel powered equipment and vessels in support of their operations. Some of this equipment has old, diesel engines that were manufactured before regulatory actions were addressed. Accordingly, ARB wanted to measure emissions from a harbor craft vessel with an older engine that is representative of those in service and unlikely to be replaced in the near future. Furthermore, ARB sought to assess the feasibility of retrofitting such an older engine with control technologies designed to reduce emissions. A key element of this project was the measurement and quantification of potential emissions benefits when using the retrofit control technologies. The University of California Riverside (UCR), working with ARB, the U.S. Navy and MARAD conducted the emissions measurement campaigns from two identical harbor craft engines: one with no emission control and one that was retrofitted with two retrofit control technologies. The emission control technologies were installed on YSD, or "Mary Anne", a barge crane used for maintaining the Naval Reserve Fleet at Suisun Bay, CA. The YSD is representative of an older harbor craft working vessel with uncontrolled diesel engines.

The YSD made use of a varying mixture of CARB diesel and salvaged diesel fuels. In this application, the properties of these fuel mixtures can change from batch to batch. In order to ensure continuity within a given set of tests, a single batch of fuel was used for both the port and starboard engines for the duration of the test period. A second batch of fuel was employed in a similar manner for the second test campaign. A sample from each of the two batches of fuel was acquired and analyzed in the laboratory to determine the fuel properties of each mixture. Analyses revealed similar fuel properties between the two batches used in the test program.

The YSD employed twin propulsion engines, one on the pot and the other on the starboard side. The high-speed diesel engines, model 12V71N, were made by the Detroit Diesel Corporation in the 1980s. These engines use two-stroke technology, and were a market share leader at that time. Because of their popularity and reliability, many of these engines are still used in harbor craft vessels today. The engines are naturally aspirated and rated at 432 hp at 2185 RPM, with a displacement of 12.96 liters each. Two emission control technologies were selected and installed as retrofits on the port engine only. The Clean Cam Technology System combines turbo-charging the original naturally-aspirated engine with in-cylinder changes to effect internal EGR, with the goal of reducing PM and NOx emissions. The Rypos active-regeneration diesel DPF traps and incinerates PM in the exhaust system. For this project, both the port (modified) and starboard (unmodified) engines were tested. Additionally, two sets of emissions samples were acquired during port engine testing: upstream and downstream of the Rypos active DPF.

**Emissions Testing: February 2006**

Emissions of NOx, CO and PM were measured over the same operating modes at three locations: engine out (upstream of Rypos active DPF) exhaust from the CCTS-equipped port engine; downstream of the Rypos active DPF in the exhaust of the CCTS-equipped port engine; and the engine out exhaust emissions from the unmodified starboard engine. Data were taken in triplicate.

*NOx Emissions*

For the baseline (starboard) engine, NOx emission factors ranged from 12.6 g/hp-hr (Mode 5) to 14.2 g/hp-hr (Mode 3). This is compared with NOx emissions from the port engine, modified with the CCTS engine retrofit technology. These emission factor ranged from 3.1 g/hp-hr (Mode 2) to 4.9 g/hp-hr (Mode 5), representing emission reductions of 61% to 77%. As expected, the Rypos active DPF had no significant effect on NOx emissions.

*CO Emissions*

For the baseline (starboard) engine, CO emission factors ranged from 0.7 g/hp-hr (Mode 4) to 5.1 g/hp-hr (Mode 3). This is compared with CO emissions from the port engine. These emission factors ranged from 1.0 g/hp-hr (Modes 2 and 3) to 2.0 g/hp-hr (Mode 4), representing emission reductions of 80% and 81% for Modes 2 and 3, respectively. For Modes 4 and 5, the CO emissions from the CCTS-modified port engine were 178% and 70% higher than the baseline starboard engine, respectively. While the Rypos active DPF was not designed to reduce CO emissions, it appeared from the downstream results that Modes 2 and 3 emissions reductions were slightly enhanced, while the Mode 4 emissions increase was mitigated by the active DPF.

*PM Emissions*

For the baseline (starboard) engine, PM emission factors ranged from 0.12 g/hp-hr (Mode 5) to 0.3 g/hp-hr (Mode 2). This is compared with PM emissions from the port engine, modified with the CCTS engine retrofit technology. These emission factors ranged from 0.11 g/hp-hr (Mode 3) to 0.34 g/hp-hr (Mode 4), representing emission reductions of 38% and 42% for Modes 2 and 3, respectively. For Modes 4 and 5, the PM emissions from the CCTS-modified port engine were 127% and 7% higher than the baseline starboard engine, respectively. The addition of the Rypos active DPF in the modified port engine exhaust resulted in PM emission factors ranging from 0.03 g/hp-hr to 0.09 g/hp-hr. Therefore, the combination of the two technologies resulted in PM emission factors that were 42% (Mode 4) and 88% (Mode 2) lower than the baseline starboard engine emissions.

**Table 7: Emissions Results: Averages (February 2006)**

| | **Mode** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| **ISO PM (g/bhp-hr)** | Baseline Starboard | 0.30 | 0.19 | 0.15 | 0.12 |
| | Upstream Port | 0.18 | 0.11 | 0.34 | 0.13 |
| | Downstream Port | 0.04 | 0.03 | 0.09 | 0.05 |
| **ISO NOx (g/bhp-hr)** | Baseline Starboard | 13.6 | 14.2 | 13.8 | 12.6 |
| | Upstream Port | 3.1 | 3.3 | 3.6 | 4.9 |
| | Downstream Port | 2.9 | 3.0 | 3.8 | 4.9 |
| **CO (g/bhp-hr)** | Baseline Starboard | 5.0 | 5.1 | 0.7 | 1.0 |
| | Upstream Port | 1.0 | 1.0 | 2.0 | 1.6 |
| | Downstream Port | 0.7 | 0.8 | 1.3 | 1.7 |

Following testing in February 2006, the vessel was returned to its normal maintenance duties at the Naval Reserve Fleet at Suisun Bay, with the port engine equipped with the CCTS retrofit engine control technology and the Rypos active DPF system. In early September 2006, the port engine exhaust system was instrumented with temperature and pressure sensors to monitor activity. The sensors were connected to data logger and the sensor signals were logged at one minute intervals over a nine week period.

**Emissions Testing: November 2006**

Following the durability period, emissions of NOx, CO and PM were again measured in a test campaign in November 2006. As in the initial test campaign, emissions were sampled over identical operating modes at three locations. Data were taken in triplicate.

*NOx Emission*

For the baseline (starboard) engine, NOx emission factors ranged from 8.8 g/hp-hr (Mode 5) to 10.3 g/hp-hr (Mode 2). This is compared with NOx emissions from the port engine, modified with the CCTS engine retrofit technology. These emission factors ranged from 3.0 g/hp-hr (Mode 3) to 4.0 g/hp-hr (Mode 5), representing emission reductions of 54% to 71%. As expected, the Rypos active DPF had no significant effect on NOx emissions.

*CO Emissions*

For the baseline (starboard) engine, CO emission factors ranged from 0.9 g/hp-hr (Mode 4) to 4.1 g/hp-hr (Mode 2). This is compared with CO emissions from the port engine. These emission factors frnaged from 0.5 g/hp-hr (Modes 2) to 1.5 g/hp-hr (Mode 5), representing emission reductions of 89% and 69%, and 6% for Modes 2, 3, and 4, respectively. For Mode 5, the CO emissions from the port engine were 25% higher than measured on the baseline starboard engine. There were no significant differences found in CO emission downstream of the Typos active PDF system.

*PM Emissions*

For the baseline (starboard) engine, PM emission factors ranged from 0.16 g/hp-hr (Modes 4 and 5) to 0.27 g/hp-hr (Mode 2). This is compared with PM emissions from the port engine, modified with the CCTS engine retrofit technology. These emission factors ranged from 0.06 g/hp-hr (Mode 3) to 0.18 g/hp-hr (Mode 5), representing emission reductions of 64%, 75%, and 34%, respectively. For Mode 5, the PM emissions from the port engine were 13% higher than the baseline starboard engine PM emissions. The addition of the Rypos active DPF in the modified port engine exhust resulted in PM emission factors ranging from 0.03 g/hp-hr (Mode 3) to 0.06 g/hp-hr (Mode 5). Therefore, the combination of the two technologies (CCTS and Rypos) resulted in PM emission factors that were 60% (Mode 5) to 90% (Mode 3) lower than the baseline starboard engine emissions.

**Table 8: Emissions Testing, Averages (November 2006)**

| | **Mode** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| **ISO PM (g/bhp-hr)** | Baseline Starboard | 0.27 | 0.26 | 0.16 | 0.16 |
| | Upstream Port | 0.10 | 0.06 | 0.11 | 0.18 |
| | Downstream Port | 0.04 | 0.03 | 0.05 | 0.06 |
| **ISO NOx (g/bhp-hr)** | Baseline Starboard | 10.3 | 10.1 | 9.7 | 8.8 |
| | Upstream Port | 3.3 | 3.0 | 3.7 | 4.0 |

| | | | | | |
|---|---|---|---|---|---|
| | Downstream Port | 3.9 | 3.2 | 3.3 | 4.2 |
| **CO (g/bhp-hr)** | Baseline Starboard | 4.1 | 1.5 | 0.9 | 1.2 |
| | Upstream Port | 0.5 | 0.5 | 0.8 | 1.5 |
| | Downstream Port | 0.7 | 0.5 | 0.9 | 1.4 |

The overall weighted emission factors were calculated based on a modified ISO 8178 E5 test cycle. As it was not possible to operate at the Mode 1 conditions, the weighting factors were normalized over 100% based on the remaining four operating modes. In addition, the Mod 5 “idle” condition was actually run at an intermediate speed under load, and therefore does not represent the true idle condition specified in ISO 8178. The overall weighted emission factor are valid for comparisons between the baseline and modified engines.

**Table 9: Weighted Emission Factors**

| | | **Emission Factor** | | | **Emission Reductions** | |
|---|---|---|---|---|---|---|
| | | **Starboard Engine (baseline)** | **Port Engine CCTS** | **Port Engine CCTS+Rypos** | **CCTS** | **CCTS+Rypos** |
| **NOx** | Feb. 2006 | 13.4 | 3.9 | 3.9 | 71.1% | 71.0% |
| | Nov. 2006 | 9.5 | 3.6 | 3.7 | 62.1% | 61.7% |
| **CO** | Feb. 2006 | 2.2 | 1.6 | 1.3 | 29.4% | 43.1% |
| | Nov. 2006 | 1.6 | 0.9 | 1.0 | 40.6% | 37.1% |
| **PM** | Feb. 2006 | 0.17 | 0.21 | 0.06 | -22.3% | 66.2% |
| | Nov. 2006 | 0.19 | 0.12 | 0.05 | 37.6 | 76.0% |

Comparative emissions show that the combination of the CCTS and Rypos retrofit control technologies have significant NOx, CO, and PM emissions benefits. The CCTS engine retrofit technology demonstrated consistent NOx reduction over all modes tested, ranging from 54% to 71%, compared with the identical unmodified engine. Significant CO reductions were found with the CCTS technology at higher loads (Modes 2 and 3), but with equal or greater CO emissions at lower loads (Modes 4 and 5), compared with the baseline engine. The CCTS technology also showed PM reductions at higher loads (Modes 2 and 3), but resulted in higher PM emissions at lower loads (Modes 4 and 5), compared with the unmodified engine. The Rypos active DPF demonstrated consistent PM reductions across all modes. The combination of the two technologies showed PM reductions of 43% to 90%.

Equally important is the finding that the emissions reductions were maintained after an approximately eight month in-use durability period. Data logging of the engine activity during the last two months of the eight month period show the engine to be operated on the frequent and regular basis.

Test results show the combination of the CCTS engine retrofit control technology and the Rypos active DPF emission control technology to be highly effective at reducing NOx, CO, and PM emissions from an older, naturally-aspirated marine diesel propulsion engine.

More information on this project is available at: http://www.docstoc.com/docs/22788307/Harbor-Craft-Retrofit-Emissions-Study.

### *3.2 Retrofitting Compact SCR and DPF on a Passenger Ferry*

An emission control system combining DPF with SCR has been developed for retrofit of diesel engines in harbor craft. The SCR system builds on the existing Compact SCR technology developed for harbor craft by Engine, Fuel and Emissions Engineering, Inc. For modern Tier II diesel engines, the Compact SCR system alone can bring both NOx and PM emissions to well within the limits specified in ARB's harbor craft emission regulations. The same is not true for the older Tier 0 diesel engines found in many California harbor craft, due to the much higher PM emission that these engines produce. The combined DPF+Compact SCR system is designed as a "bolt on" retrofit for these older Tier 0 diesels, and to reduce their emissions to below Tier 4 limits. For Tier 0 engines that are otherwise in good condition, this technology is expected to be both less expensive and more effective than repowering with new diesels meeting Tier 2 or Tier 3 emission standards.

The Compact SCR+DPF systems are being demonstrated on M/V *Royal Star*, a passenger ferry and excursion vessel owned and operated by Blue and Gold Fleet of San Francisco. Installation of the demonstration system on M/V *Royal* Star, an 800 passenger ferry began in May 2009. The main propulsion engines on this vessel are two Caterpillar 3412 diesels rated at 520 hp each, while the generator engines are two Caterpillar D377s. The generators are rated at 50 kW each. As of April 2010, the Compact SCR system and main engine DPFs have undergone about 450 hours of operation, beginning in September 2009. The DPFs for the generator engines were installed only in April 2010, and have not yet been subjected to operation. M/V *Royal Star* in April 2010 was out of service, undergoing repairs to her marine gearing, and EF&EE was taking advantage of this interlude to revise the electric regeneration system for the DPFs. The full system, comprising Compact SCR and DPF installations on both main engines and both generators, was expected to go into operation when the vessel returns to service at the end of April 2010.

An emission control retrofit system for marine vessels must satisfy U.S. Coast Guard safety requirements in addition to ARB's requirements for emissions verification. It must be ensured that the emission control system does not cause a fire aboard the vessel. Except for tugs, most marine vessels operate at near-full power under cruise conditions, so that the exhaust temperature can reach 400°C to 500°C. Coast Guard regulations require that the exhaust system be fully insulated for fire and personnel safety. It must also ensure that any emission control system failure does not disable the engine.

Because they operate much of the time at full power, marine engines are much more sensitive to exhaust backpressure than are engines in trucks and similar applications. Therefore, DPFs and SCR catalysts for marine engines need to be larger than those used for truck engines of similar rated power. Since available DPFs and Compact SCR catalysts were sized for truck engines, multiple parallel DPF/catalyst elements were required.

A key design decision in this project was whether to place the DPF elements ahead of or behind the SCR catalysts. Placing the DPF elements ahead of the SCR catalyst keeps the catalyst modules from being fouled and possibly plugged by soot. It also increases the temperature of the exhaust entering the DPF, thus increasing the chance of passive regeneration.

If the DPF uses a platinum catalyst, it will convert a substantial fraction of the NO passing through to $NO_2$, which improves the kinetics of the SCR reaction. However, it runs the risk of heat damage to the SCR catalysts if the exhaust temperature out of the DPF exceeds 650°C.

This emission control system is intended for use with older engines having relatively high PM emission. Therefore, the risk of clogging the SCR catalysts if they were located upstream of the DPFs was the deciding factor. To mitigate the risk of overheating the SCR catalysts during regeneration, they elected to use multiple DPFs for each engine, and to regenerate each DPF separately. The hot exhaust from the DPF undergoing regeneration would be diluted by the cooler exhaust passing through at least one other DPF. This led the demonstrators to choose electric resistance heating as the assisted regeneration method for the DPFs.

Locating the SCR catalyst downstream limited the space available for mixing between the urea injection point and the SCR catalysts. Urea could not be injected upstream of the DPFs, as the non-selective precious metal catalysts on the DPF would oxidize the ammonia. To make best use of the available space, the urea injector was incorporated into the DPF mounting assembly. To ensure that failure of the DPF regeneration system could not lead to engine shutdown due to excessive backpressure, the DPF assemblies were provided with bypass valves for safety. These bypass valves were designed to open if the backpressure across the DPF assembly exceeded 100 millibar.

Working with the Danish firm Cometas A/S, EF&EE tested several catalyst formulations. The first and most aggressive formulation was effective assuring passive regeneration of the DPF under test conditions, but converted too large a fraction of the NO emissions from the engine to $NO_2$. While the SCR catalyst reduced the rate of $NO_2$ emissions, the increase due to the DPF more than offsets this. The DPF supplier was able to offer two catalyst formulations with less tendency to convert NO to $NO_2$. The first of these, called NO2P by the supplier, used a reduce amount of precious metal catalyst in combination with a base metal. The second formulation, NO2X, used only the base metal catalyst. In addition to eliminating the $NO_2$ conversion problem, the second formulation was also less expensive but less effective in promoting DPF regeneration. Because it was unclear which of these two formulations would be preferable, EF&EE opted to test both in this demonstration project. The NO2P formulation was used on the DPFs for the Port main engine and generating set, while the NO2X formulation was used in those for the Starboard.

For most diesel boats under cruise conditions, the main propulsion engines operate at high load for substantial periods of time. Given this operating pattern, it was anticipated that the DPFs installed on the main engines would undergo frequent passive regenerations, so that the active regeneration system would be needed only as a backup. In contrast, the generator engines on most diesel boats are very lightly loaded most of the time. Therefore, it was expected that DPF regeneration on these engines would nearly always require active regeneration.

Most DPF retrofit systems used on trucks rely on diesel fuel burners or catalytic combustion of diesel fuel in the exhaust for regeneration. For a passenger vessel, where the DPF system was located below decks, these approaches were considered to present an unacceptable risk of fire. Since such vessels are almost always equipped with diesel generating sets, electric resistance heating was considered a safer and more attractive option. For regeneration of the gensets' own DPF, electric resistance heating has the extra advantage that it adds to the load on the generator, increasing the engine-out exhaust temperature. The initial design for the regeneration system was to use the DPF itself as the ceramic support for the electric resistance wire, by wrapping that wire around the DPF between it and the intumescent mat used to hold the DPF in its metal shell or "can". This approach proved unworkable with the silicon carbide DPFs, as the grade of silicon carbide used in the prototypes became conductive at temperatures around 300°C and short-circuiting the heater. This made it necessary to redesign the DPF mounting assemblies to accommodate electric heating elements in front of the DPF itself.

Except for the DPF modules and regeneration system, the Compact SCR+DPF system was installed in M/V *Royal Star* in May 2009. The requirement to redesign the regeneration system meant that the DPF modules could not be installed in the DPF assemblies for the main engines until late September 2009, while those for the generators were installed in April 2010. The Compact SCR systems on *Royal Star* were active beginning in early September 2009. M/V *Royal* Star was in frequent use from Labor Day weekend through October 31, during which time she accumulated more than 350 engine operating hours. The Compact SCR system was active nearly all of the time from September 8 through October 31, so that the cumulative catalyst-out emissions during this time grew only slowly. The vessel then underwent a prolonged period of very little use that lasted through mid-January. Following the long shut-down in November, the self-diagnostic system showed that the urea injector was plugged, probably due to urea solution drying out in the line.

As of April 201, due to software and wiring issues, the controls for the electric heaters used for DPF regeneration had not been activated, so that the main engine DPFs were subject only to passive regeneration from the end of September 2009 through April 2010. Given the high load experienced by the main engines under cruise conditions, it was anticipated that the DPFs would undergo passive regeneration frequently. However, analysis of the exhaust pressure and temperature data logs showed no evidence of passive regeneration in the Starboard DPF assembly, and only a single identifiable regeneration event in the Port DPF assembly. Instead, it appeared that the DPFs were filled with soot to the point that the bypass valves opened at high load. The combination of slow oxidation of the soot in the DPFs and the bypass valve opening at high load, the DPF loading appeared to have reached and maintained a steady state, but one that allowed a significant amount of PM to bypass the DPFs under cruise conditions.

Preliminary emission testing was conducted on the Starboard main engine on September 9, 2009. Table below shows measured emissions in grams per kWh at the 100%, 75%, and 50% load points, corresponding to 1800, 1720, and 1650 RPM, respectively. For the pre-control data, the 25% load point is also shown. Due to scheduling issues with the vessel crew, there was insufficient time to collect the post-control data at the 25% load point.

**Table 10: Starboard Main Engine Emissions vs. Load, Pre- and Post-Emission Control System**

| Load | Emissions (g/kWh) | | | | | |
|---|---|---|---|---|---|---|
| | PM | | NOx | | CO | |
| | Pre | Post | Pre | Post | Pre | Post |
| 100% | 0.341 | 0.188 | 5.201 | 0.801 | 1.122 | 0.054 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 75% | 0.339 | 0.208 | 4.910 | 0.577 | 1.315 | 0.177 |
| 50% | 0.418 | 0.096 | 5.256 | 0.517 | 1.355 | (0.075) |
| 25% | 0.205 | | 5.260 | | 0.690 | 0.000 |
| EPA Wtd. | 0.331 | 0.169 | 5.072 | 0.614 | 1.189 | 0.057 |

As Table 7 indicates, PM emissions from this engine were moderately high, reaching 0.418 g/kWh at 50% load. The PM control efficiency was 78% at the 50% load point, but dropped to less than 50% at the higher loads. This is about the control efficiency that would be expected from the SCR catalyst alone, and indicates that much of the exhaust must have been bypassing DPF at these loads.

The NOx control efficiency was much better, ranging from 85% at full power to 90% at the 50% power condition. CO emissions were reduced by about 95% overall.

EF&EE's competitive analysis showed that there is a small but rapidly-growing market for SCR systems in commercial boats. EF&EE believes that once the DPF regeneration issues are resolved, the SCR+DPF system on M/V *Royal Star* will demonstrate the achievement of similar emission levels starting with 20-year old Tier 0 engines.

More information on this is available at: http://www.arb.ca.gov/research/apr/past/icat06-04.pdf.

### *3.3 San Francisco Ferry Demonstration*

The ferries Gemini, Pisces, Scorpio, and Taurus were all equipped with Compact SCR systems by EF&EE on their 1410 hp main engines. All four boats were ordered by the Water Emergency Transit Authority (WETA) for service in San Francisco Bay. To mitigate the environmental impact of the new ferry services, the WETA specification required cruise emissions from the new boats to be 85% below Tier 2 levels. Acceptance testing showed the actual emissions to be 96% below Tier 2, and within EPA Tier 4 emission limits. NOx was reduced by 97% and PM by about 60% compared to engine-out emissions.

**Table 11: Emissions Testing Results**

| **Acceptance Testing Data** | **M.V. *Pisces* (g/kWh)** | | **M.V. *Gemini* (g/kWh)** | | **M.V. *Scorpio* (g/kWh)** | |
|---|---|---|---|---|---|---|
| **85% Power Cruise** | **Port Main** | **Stbd Main** | **Port Main** | **Stbd Main** | **Port Main** | **Stbd Main** |
| NOx (measured) | 0.18 | 0.28 | 0.01 | 0.18 | 0.24 | 0.28 |
| PM (measured) | 0.023 | 0.022 | 0.048 | 0.021 | 0.023 | 0.026 |
| CO (measured) | 0.02 | 0.03 | 0.04 | 0.10 | 0.09 | 0.08 |
| HC (estimated) | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Total NOx+PM+HC w/ SCR | 0.22 | 0.32 | 0.08 | 0.22 | 0.29 | 0.33 |
| NOx+PM+HC WETA Contract Requirements | | 1.11 | | | | |
| NOx+PM+HC EPA Tier 2 Emission Standards | | 7.4 | | | | |

More information on this is available at: http://www.efee.com/scr.html.

## 4.0 SUMMARY

As shown by the above case studies, experience with the application of emission control technologies on locomotive and marine diesel engines is growing. Many of the locomotive and marine diesel engine projects discussed in this report have been focused on demonstrating the feasibility of applying verified, on-road retrofit emission control technology on locomotive and marine engines and quantifying the diesel emission reductions achieved. Many of the projects have been initiated by the state, local, and federal agencies to promote interest in retrofitting locomotive and marine engines and facilitate other retrofit projects that may build on the successes and challenges learned from previous projects. The availability of ULSD fuel for nonroad diesel engines has expanded significantly as the rollout of ULSD for highway applications expanded nationwide after its introduction in the second half of 2006. Emerging on-road verified retrofit technologies, such as actively regenerated DPFs and flow-through particulate filters, should also find applications in nonroad diesel engines and provide more options for significant reductions in diesel particulate emissions from locomotive and marine engines. Similarly, verified retrofit technologies that provide reductions in NOx emissions, such as lean NOx catalysts and SCR systems, will also migrate into the nonroad sector and see greater attention on locomotive and marine engines in the future. The locomotive and marine engine segments require an expanded range of verified retrofit technologies to provide broader application coverage for the range of engines that are currently part of the existing fleet.

The growing experience base with DOCs, DPFs, and SCR on locomotive, marine, and stationary diesel engines indicates that these technologies are feasible for use on new locomotive and marine engines and can provide significant reductions in PM and NOx emissions from these sources compared to their current emission standards. These technologies will all play significant roles in achieving future EPA Tier 4 emission standards for locomotive and commercial marine diesel engines.