

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

September 2009



Manufacturers of Emission Controls Association

1730 M Street, NW * Suite 206 * Washington, DC 20036

www.meca.org

www.dieselretrofit.org

Table of Contents

| | | |
|------------|---|-----------|
| 1.0 | Introduction..... | 1 |
| 2.0 | Locomotive Case Studies..... | 3 |
| 2.1 | California Emissions Program | 3 |
| 2.2 | Union Pacific and Progress Rail Services Locomotive Project | 5 |
| 2.3 | Southwest Research Institute Locomotive Retrofit Project | 5 |
| 2.4 | Metrolink Passenger Locomotive SCR Project | 6 |
| 2.5 | DPF Applications for New and Retrofit Locomotives in Switzerland and Europe | 6 |
| 2.6 | GE Locomotive Retrofit Program..... | 6 |
| 2.7 | Massachusetts Bay Transportation Authority Locomotive Demonstration Project | 8 |
| 2.8 | California Advanced Locomotive Emission Control System Project..... | 8 |
| 2.9 | Retrofit of Head End Power Units on Commuter Rail Locomotives | 10 |
| 2.10 | Demonstration of DPFs on a Gen-Set Switch Locomotive | 10 |
| 3.0 | Large Marine Engine Case Studies..... | 11 |
| 3.1 | New York Harbor Private Ferry Emissions Reduction Program..... | 11 |
| 3.2 | Staten Island Ferry Emissions Reduction Demonstration Project | 12 |
| 3.3 | San Francisco Bay Harbor Craft..... | 13 |
| 3.4 | San Francisco Ferry Retrofit Project..... | 13 |
| 3.5 | U.S. Navy Work Boat/Barge | 13 |
| 3.6 | Holland America Seawater Scrubbing Technology Feasibility Study | 13 |
| 3.7 | Marine Experience in Europe and Asia | 14 |
| 4.0 | Funded Projects | 14 |
| 4.1 | American Reinvestment and Recovery Act of 2009..... | 14 |
| 5.0 | Retrofit Verifications for Marine Engines..... | 15 |
| 6.0 | Summary..... | 16 |

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 (NO_x), 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 NO_x 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 NO_x 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 particulate matter (PM) emissions, and lean NO_x catalysts and selective catalytic reduction (SCR) catalysts for reducing NO_x emissions.

The extensive international experience base of SCR for controlling NO_x emissions from stationary sources has been used over the past 15 years to develop NO_x 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 are now commercially available in Europe where hundreds of thousands of units are operating on the roads to comply with Euro 4 and Euro 5 heavy-duty engine emission regulations. SCR is being 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 NO_x (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 NO_x from stationary sources and large marine diesel engines for over 20 years.

A recent 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/lchu.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% NO_x, 90% CO, and 75% HC, with less than 0.01 ppm ammonia slip. Many other stationary diesel engines have successfully achieved significant reductions in NO_x 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 NO_x reduction technology originally developed for stationary engines has been successfully adapted to on-road vehicles and marine applications in Europe and suggests 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). In June 2009, EPA proposed a more stringent exhaust emission standards for the largest marine diesel engines used for propulsion on ocean-going vessels (Category 3 engines). EPA is proposing additional emission control standards for these engines because of the opportunity to achieve significant public health benefits and the improved feasibility of applying high efficiency emission control technologies to these engines. The proposed engine standards are equivalent to NO_x limits recently adopted in amendments to International Maritime Organization's MARPOL Annex VI regulations. The growing list of examples of the application of advanced diesel emission controls to locomotive and marine diesel engines outlined in this report provides technical support for significantly tighter emission standards for these important mobile emission sources.

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. In 2009, EPA and Canada proposed to create a special Emissions Control Area (ECA) near their coastlines. EPA proposed a mandatory 0.1% fuel sulfur limit on ocean-going vessels operating in U.S. waters starting in 2015. Ships entering an ECA must eventually reduce NO_x emissions by 80%, PM by 85%, and SO_x by 95% compared to current limits. Given the health and environmental concerns associated with diesel engines and because the non-road engines make up a significant percentage of diesel pollution emitted, there is an increasing interest in retrofitting older non-road diesel 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, NO_x, and SO_x from vessels operating within 24 nautical miles of the California coastline. 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. In addition, ARB has signed an agreement with the railroad industry and the EPA to implement an averaging program in the South Coast region, where locomotives meeting the 2005 EPA standards will be in place by 2010. California's aggressive goods movement related initiatives include significant focus on mediating emissions from ports and railyards, including emission reductions from locomotives and marine diesel engines (see: www.arb.ca.gov/gmp/gmp.htm). In addition, in August 2009, ARB released a revised technical evaluation of 37 options that may accelerate further statewide locomotive and localized locomotive and non-locomotive railyard emission reductions. This technical evaluation of each option addresses the technical feasibility, potential emission reductions, costs and relative cost-effectiveness. A copy of the revised report is available at: <http://www.arb.ca.gov/railyard/ted/ted.htm>.

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 *California Emissions Program (CEP)*

In 2001, the California Air Resources Board (ARB), Union Pacific Railroad (UP), and BNSF Railway (BNSF) entered into a voluntary agreement to evaluate the feasibility of installing diesel particulate filter (DPF) technology in locomotives. With direction from ARB,

the Association of American Railroads (funded by UP and BNSF) has overseen the California Emissions Program (CEP), with Southwest Research Institute (SwRI) leading the effort to evaluate candidate retrofit DOC and DPF systems. The engine that was chosen for retrofit is a 1,500 hp EMD MP15DC switcher locomotive engine. Below is a summary of SwRI's work:

- SwRI has screened commercially available cylinder kits to identify those that offered the lowest lubricating oil consumption. Rebuilding the EMD engines with cylinder kits that use less lubricating oil will produce lower engine-out PM emissions, reduce the burden on any retrofit system, and will reduce the lubricating oil ash loading on the retrofit device.
- CEP focused on evaluating DOC and DPF systems for locomotives using conventional non-synthetic lubricating oil and low oil-consumption power assemblies. SwRI screened more than 14 DOC and DPF candidates on the engine.
- SwRI tested for engine performance and 500-hour system durability for three candidate retrofit systems in an engine test cell.
- SwRI has performed emissions testing in a test cell and will conduct in-use emissions testing.
- CEP screening test showed that an actively regenerated DPF technology that utilizes a diesel burner for soot regeneration and SiC wall-flow filter elements was the best currently available device.
- The first two 1,500 hp switchers that were retrofitted with the selected, active DPF technology were scheduled for revenue testing (testing in actual freight service instead of on a test track) in southern California beginning in July 2006. In addition to the active DPF systems, these switcher locomotives were also installed with automatic stop/start devices that reduce the PM output of the locomotives during engine operation at idle. Additional locomotive retrofits may result from this program.

The selected DPF (active regeneration using a diesel fuel burner) was installed on a UP switcher locomotive in October 2006 and has been in service for 32 months, accumulating 5,766 running hours as of May 2009. During the demonstration period, some issues were encountered:

- Trapping efficiency is below desired levels
 - Initial efficiency was approximately 80%. Had expected 90 to 95% efficiency
- White smoke at regeneration after extended idle caused by oil and fuel build up on "dirty" side of filter.
 - Burning off of oil and fuel causes white smoke
- Burner ignition reliability

The active DPF was also installed on a BNSF switcher locomotive. This DPF experienced some mechanical mounting problems during operations.

More information on this project is available at:
www.arb.ca.gov/railyard/rsubmittal/dpf_sum.pdf.

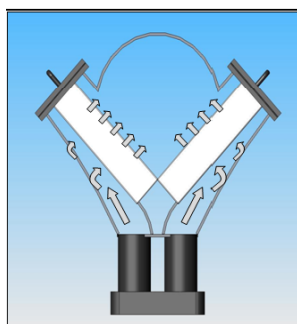
2.2 *Union Pacific and Progress Rail Services Locomotive Project*

In May 2009, Union Pacific Railroad and Progress Rail Services launched initial operation of an ultra clean diesel SD40-2 locomotive equipped for intermediate line haul service. The Progress Rail PR30C-LoNox locomotive has been repowered with a single 3,005 hp, low-emission diesel engine and meets EPA's Tier 2 standards. The engine is equipped with a DOC+SCR system and will run between the railroad's San Antonio and Fort Worth service units. The locomotive is expected to reduce NOx emissions by more than 90% from the original 1970s vintage engine. The durability and performance of the DOC+SCR will be closely monitored and evaluated over a six-month period to ensure safe and dependable operations. More information on this project is available at:

http://www.uprr.com/newsinfo/releases/environment/2009/05_21_ultra_clean_diesel.shtml.

2.3 *Southwest Research Institute Locomotive Retrofit Project*

The Southwest Research Institute (SwRI), in cooperation with Union Pacific Railroad, U.S. EPA and a catalyst manufacturer, initiated a project to demonstrate retrofit of an experimental DOC on a Tier 0 line-haul EMD SD60 locomotive built in 1989 and powered by an EMD 16-710-G3A cylinder engine. This was the first retrofit project retrofitting a DOC on a high horsepower freight locomotive in the U.S. The experimental DOC is an in-manifold design (see figure below). An on-board datalogger was installed to continually monitor and record operational parameters during revenue service. The line-haul locomotive was placed into service in California in October 2006. Baseline emission testing indicated that the DOC could reduce diesel PM by up to 50%. However, the three-month inspection of the DOC revealed a minor mechanical problem with the catalyst elements that was quickly repaired. The locomotive was returned to SwRI in April 2007 for a second inspection and six-month emissions test. The inspection revealed mechanical failures of the catalyst frame. The catalyst elements were pulled out and the locomotive was returned to service without the DOC. The catalyst manufacturer redesigned the catalyst frame and the DOC was reinstalled in June 2007. The redesigned DOC accumulated 1,163 hours of operation as of October 2007. Another inspection of the DOC showed the turbo screen plugged with DOC debris and two of 16 catalyst elements were damaged. All 16 catalyst elements were removed and sent to the catalyst manufacturer. The catalyst manufacturer developed an improved V-Cat design and delivered the assembly to SwRI in May 2008. The locomotive performed successfully over the next six month timeframe, and the same DOCs used on the line-haul locomotive have been retrofitted on two Canadian passenger locomotives.



In-manifold DOC design

2.4 Metrolink Passenger Locomotive SCR Project

Metrolink operates 38 EMD F59PH and F59 PHI locomotives in commuter rail service throughout the South Coast region in California. Under a grant agreement approved by the AQMD Board on September 8, 2006, Metrolink is demonstrating a SCR system on a locomotive main propulsion engine. The retrofitted locomotive is being tested along three of Metrolink's inter-regional routes to demonstrate SCR function under different operational conditions, including tunnels and grades. A SCR system was retrofitted on a EMD F59PH main propulsion engine of a Metrolink passenger locomotive. This and similar two-stroke diesel engines are also widely used on EMD freight locomotives. The SCR system design was improved upon to include: stronger housing; increased support; flexible turbo coupling; and a revised urea injection schedule. The SCR system was installed on February 2009 and after 600 hours, the substrate cracked due to resonance at idle. The SCR catalysts were reinstalled and have been in operation since May 2009. SCR emission testing was performed after 100 hours of operation:

| | NOx (g/hp-hr) | PM (g/hp-hr) | HC (g/hp-hr) |
|-------------|---------------|--------------|--------------|
| Baseline | 9.2 | 0.34 | 0.2 |
| SCR | 2.6 | 0.08 | 0.0 |
| % Reduction | 72 | 76 | 100 |

Ammonia slip < 5 ppm, low levels of N₂O
Urea rate at 6% of fuel consumption

The SCR system will be monitored for one year and on-board emission tests will be conducted throughout the demonstration period. More information on this is available at: <http://www.arb.ca.gov/railyard/ryagreement/ryagreement.htm#pubmtg>.

A DPF+SCR system was also retrofitted on a Metrolink HEP EMD F59PHI locomotive. The Head End Power (HEP) unit provides passenger hotel power and accounts for about 25% of the emissions due to continuous full power operations. The DPF+SCR system was installed with electronic controls, datalogger and dial-up link in February 2009 and baseline and degreened testing was completed in May 2009. Several design modifications were made:

- System was reprogrammed to stop urea injection at 500°C. Below 500°C, the system is reducing NOx by 88-93%.
- During maintenance, the DPF clogged due to low temperature yard operation. The DPF bricks were replaced.

A 1,000-hr emission testing effort will start in September 2009. More information on this project is available at: <http://www.arb.ca.gov/railyard/ryagreement/ryagreement.htm#pubmtg>.

2.5 DPF Applications for New and Retrofit Locomotives in Switzerland and Europe

Switzerland has initiated a program to install DPF technologies on its fleet of diesel-hydraulic freight locomotives. The primary focus in Switzerland was the application of DPFs for new, low horsepower (2,000 hp) switcher locomotives. Switzerland has also retrofitted six existing 1,200 hp engines with DPF systems. Swiss rail freight is operated by SBB (the Swiss Federal Rail System). Of the 603 total locomotives used to move freight in Switzerland, 113 are

diesel powered, and, of those, 73 new, low horsepower units are fitted with DPFs, while 6 of the 40 existing low hp units have been retrofitted with DPFs.

Vossloh 1700 Series Locomotive (Am843 in Switzerland)

Vossloh Locomotive GmbH (Vossloh) is the major diesel-hydraulic locomotive manufacturer in Europe and produces the MaK1700 series locomotive (identified as Am843 in Switzerland) that is powered by a Caterpillar 3512 4-stroke diesel engine (1,500kW/2,000 hp). In 2004, SBB started delivery of new 73 Am843 locomotives and required that all locomotives in this series be equipped with DPFs. Only synthetic engine lube oil (low ash) can be used with this engine and low-sulfur (<300 ppm) diesel fuel is used. No in-use exhaust emissions testing was performed or was required, so it is difficult to assess the actual reductions achieved.

Vossloh Am841 Locomotives

The 1,200 hp Am841 locomotive is the smaller predecessor to the Am843 and is equipped with MTU 396 engines without DPFs. Currently, there are 40 of these locomotives operating in Switzerland. SBB recently retrofitted 6 of the units with actively regenerated DPFs (burner-based regeneration): for the first three prototypes, the DPFs were added to the roofs of the locomotives, downstream of the existing muffler; for the next three retrofits, the DPF was packaged within the carbody, replacing the mufflers. Only synthetic engine lube oil (low ash) can be used with this engine and low-sulfur (<300 ppm) diesel fuel is used. No in-use DPF exhaust emissions testing is planned for these locomotives retrofitted with the DPFs.

New Vossloh 2000 Prototype Locomotive

The MaK2000BB is a new prototype for high horsepower (3,600 hp) locomotives equipped with an MTU 20V-400 engine that was built with an actively regenerated DPF integrated into the carbody. The locomotive has a DPF integrated into the original design that replaces the muffler and two burners are used to regenerate the filter. No emissions test has been performed. The DPF is offered as an option on this new locomotive in selected European markets and, to date, none have been ordered.

More information on this project is available at:
www.arb.ca.gov/railyard/rsubmittal/dpf_sum.pdf.

2.6 GE Locomotive Retrofit Program

GE Locomotive Retrofit Program, made up of consortium members and managed by GE Canada, aims to develop and demonstrate a retrofit emissions control package for use on diesel locomotives. The program is funded by Sustainable Development Technology Canada. GE Canada and its partners will incorporate a DPF targeted to reduce PM emissions by more than 85% from U.S. EPA Tier 2 emission standards. SCR technology will also be integrated into the locomotive to reduce NOx emissions by more than 65%. The project will also utilize biodiesel fuels to demonstrate compatibility with NOx and PM emissions reduction technology. CN Rail will host the Clean Diesel Locomotive project on its newer GE locomotives used both in Canada

and the U.S. CP Railways will host the project to modernize old EMD SD40-2 locomotives, expecting to reduce NOx by 24%, HC by 29%, GHGs by 20%, and improve fuel and lube oil consumption. CN Rail will also test the DPF and biodiesel on the modernized EMD locomotives. More information on this project is available at:

www.sdte.ca/en/news/media_releases/Projects_RD11.htm.

2.7 *Massachusetts Bay Transportation Authority (MBTA) Locomotive Demonstration Project*

In 2004, as part of the Locomotive Demonstration Project, the MBTA installed a diesel oxidation catalyst (DOC) on a diesel-powered commuter rail locomotive as a replacement for the sound attenuator. The DOC was installed on a GM EMD 645E3, 16 cylinder two-stroke diesel locomotive engine. The goals of this project were:

- To demonstrate that a DOC can reduce PM emissions from heavy-duty diesel locomotive engines;
- Quantify baseline exhaust emissions and emissions following the application of cleaner fuel and the DOC;
- Assess the durability of a DOC for normal use in locomotive operations; and
- Determine the steps needed to commercialize the use of catalysts in locomotive operations.

Emissions testing was conducted and showed that the DOC reduces HC emissions by 16% and PM emissions by 47%. However, three weeks after putting the retrofitted locomotive back into service, engine problems emerged. After removing the DOC, it was found that the DOC was plugged with wet soot, which led to back pressure on the engine and operational problems that caused more PM emissions and further plugging (“cascade” failure).

In October 2005, the commuter locomotive was retrofitted with a close-coupled oxidation catalyst. The DOC was placed within the exhaust manifold between the engine and turbocharger, where the exhaust temperature is substantially higher and the exhaust pressure is greater and less sensitive to backpressure. The DOC is expected to reduce PM emissions by 25% to 45%. In December 2005, the locomotive was taken out of service for normal maintenance and to check the DOC. After 900 hours of durability testing, the DOC showed no signs of plugging, but the thermal and vibration stress cause some physical degradation on the DOC. In January 2006, the redesigned catalyst was installed and ran for 45 days. Emission testing was conducted in March 2006. This demonstration project showed that a DOC can be located between the engine and turbocharger.

More information on this project is available at: www.northeastdiesel.org/pdf/EPA-NE-RR-Jan-2006.pdf.

2.8 *California Advanced Locomotive Emission Control System Project*

Placer County Air Pollution Control District, with other partners, including the U.S. EPA, the Sacramento Municipal Air Quality Management District, Union Pacific Railroad, and

Advance Cleanup Technologies, has initiated a project to employ selective catalytic reduction (SCR) technology on locomotives operating at the Roseville, California railyard (near Sacramento). This project was initiated to demonstrate an Advanced Locomotive Emission Control System (ALECS) at the Roseville railyard to control diesel emissions from locomotives. The initial project emissions mitigation plan will make use of stationary air pollution control devices to capture and treat emissions from stationary locomotives that are idling or undergoing engine load tests. The project aims to demonstrate the effectiveness of stationary air pollution control devices (primarily flue gas scrubbers + SCR) in reducing PM, NO_x, SO_x, and VOC emissions from locomotive engines. The project is developing a locomotive-specific interface (an exhaust bonnet on a moveable overhead rail system) for capturing the locomotive engine exhaust and directing it through the emission control system. First tests of this system using stationary and slow-moving locomotives to evaluate the effectiveness of the control device began in August 2006. The project is being implemented over two phases: 1) The first phase, initiated in September 2005, was to develop the locomotive interface design, test location definition and design, develop test protocols, and acquire locomotive interface hardware. 2) The second phase shipped the ALECS to the Roseville railyard, erected the ALECS on the test site, started-up the ALECS equipment, tested two different locomotive types using the developed test protocols. The preliminary locomotive testing demonstrated ALECS has potential control efficiencies of up to 90% or more for NO_x, PM and other pollutants.

ALECS has not been subject to full-scale railyard demonstration testing. Full-scale railyard demonstration testing is needed to determine the potential utilization rates and emissions reductions within actual railyard operations. Another reason for the demonstration testing is to determine what effects, if any, the ALECS system would have on the timeliness and effectiveness of railyard operations. ALECS started a full-scale demonstration project at the UP Roseville railyard in early 2009, and is expected to be completed in mid-2010. This demonstration testing will primarily focus on the potential to reduce railyard service and maintenance diesel PM emissions. Service and maintenance areas are where the greatest number of locomotives operate in idle or are stationary for diagnostic testing purposes with rolling locomotives, but are limited to a total system length of about 1,200 feet.

More information on this project is available at:
www.arb.ca.gov/railyard/ryagreement/071306placer.pdf.

A similar approach has been implemented at a railyard on the outskirts of Paris by the French national rail company, SNCF. In this system, a combined DPF + urea-SCR stationary system has been installed with an overhead exhaust bonnet set-up to capture and treat the exhaust of locomotives as they start-up and idle before beginning service. Diesel locomotives that operate out of the Paris-East rail station are shuttled from Paris-East by an electric switcher locomotive to the facility on the outskirts of Paris where the emission control system is located to lower emissions in the vicinity of the densely populated Paris-East station. The DPF + SCR system provides reductions in hydrocarbons, CO, PM, and NO_x for the locomotives engines that are started-up at this facility. This system was put in place and began operating in the spring of 2006. Details of the SNCF emission control system near Paris are available at:
www.arb.ca.gov/railyard/ryagreement/071306fritz2.pdf.

The use of a stationary emission control treatment facility that employs DPFs and urea-SCR has also been discussed for reducing emissions from large marine vessels docked at a port facility. Again, in this port scenario, a barge equipped with or dockside location of an emission control system could be employed with an exhaust capture bonnet to reduce ship emissions associated with auxiliary engines operated onboard the ship when it is docked at a wharf. This port clean-up concept would be especially well suited to deal with port emissions from existing ships that may be difficult to retrofit with emission control technologies because of space constraints onboard the vessel. The ALECS technology evaluated at the Roseville railyard was also evaluated at the Port of Long Beach for reducing emissions from large ships berthed at the port in late 2006 into early 2007.

2.9 *Retrofit of Head End Power Units on Commuter Rail Locomotives*

On February 24, 2005, the Sacramento Metropolitan Air Quality Management District (SMAQMD) received a grant under the National Clean Diesel Campaign to install emission control devices on two commuter rail locomotives owned by Amtrak that run between Oakland and Sacramento, CA.

The goal of this project is to install an air pollution control retrofit technology in an innovative application in order to achieve significant emission reductions from a locomotive heavy-duty diesel application. This demonstration project will retrofit 13 Head End Power (HEP) engines in passenger cars used in the Capitol Corridor service that have very large heating/ventilation/air conditioning electrical loads, as well as significant lighting, power strip, and concession stand power demands. The Capitol Corridor HEPs are Tier 1 Caterpillar 3412 engines rated at 1080 horsepower, operating 5,000 hours per year at an average of 300 kW load, resulting in emissions of NO_x+PM+VOC totaling 12.08 tons per year per engine. The retrofit technology that will be installed on the HEP engines will be a device that is ARB verified for on-road applications. The retrofit device consists of a lean NO_x catalyst and a DPF that is verified to reduce PM by 85% and NO_x by 25% for on-road diesel engine applications. This project will demonstrate the innovative use of the ARB verified diesel retrofit technology in a non-verified application and will assist in demonstrating the commercial viability of the retrofit technology for locomotive applications. It is estimated that the retrofit of the 13 HEP engines will achieve a total of 217 tons of NO_x+VOC+combustion PM for a five-year project life.

More information on this project is available at:
www.westcoastdiesel.org/files/meetings/2005-03-21/5a - Locomotives.ppt.

2.10 *Demonstration of DPFs on a Gen-Set Switch Locomotive*

Brookville Equipment Company recently installed a passive DPF system on a prototype three engine gen-set switch locomotive built with three Tier 3 nonroad engines. Brookville installed a passive DPF system that relied on locomotive exhaust temperatures to burn away ash and carbon buildup on the DPF. During field testing, Brookville began to experience ongoing ash buildup and cleaning problems with the passive DPF system. Brookville chose for the time being to remove the passive DPF system from the gen-set switch locomotive during field testing.

3.0 LARGE MARINE ENGINE CASE STUDIES

3.1 *New York Harbor Private Ferry Emissions Reduction Program*

Due to the resurgence of ferry ridership in the New York City harbor area and the region's designation as a NO_x non-attainment area, there is a pressure on the ferry operators to reduce air pollution emissions. As a result, the New York State Energy Research and Development Authority (NYSERDA) has initiated a \$6.8 million program to collaborate with private ferry operators to demonstrate emission reduction technologies. Currently, there are approximately 50 private passenger ferries operating in the harbor. In September 2003, Seaworthy Systems, Inc. was awarded with a prime contract to oversee the implementation of the demonstration program, with assistance from Environment Canada, Northeast States Coordinated Air Use Management (NESCAUM), and ESI International. The goals of this project are to:

- Reduce private ferry fleet emissions
- Focus on NO_x reduction as well as particulate matter (PM_{2.5})
- Aim at near term results instead of new boat construction
- Ultimate widespread deployment

Three local ferries that agreed to participate are: New York Waterways, Inc.; SeaStreak, Inc.; and New York Water Taxi, Inc. However, SeaStreak later withdrew from the program due to business reorganization issues. The scope for Phase I of the project consists of fleet characterization; emissions control technology analysis, ranking, down-selection; and demonstration of three to five selected technologies. Phase II consists of providing an estimated \$5 million for incentivizing the private fleets to install the selected technologies. This multi-year program helped to provide credible information on the costs, benefits, and feasibility of a wide range of possible emissions control options from private ferry fleets, as well as real-world experience with the use of the identified "best choice" emissions control technologies.

During the Phase I of the project, a technology review was performed to eliminate experimental or pre-production technologies and focus on commercially available products that promised significant reductions of NO_x and PM_{2.5} for the specific operating conditions of the diesel engines. Technologies that are selected for demonstration are:

- DOC plus fuel-borne catalyst installed on CAT 3412E vessels.
- SCR plus DOC installed on Cummins KTA50M2 engines.
- DOC on Detroit Diesel Series 60 engines.
- DOC plus Continuous Water Injection System installed on CAT 3406E or 3412C engines. The water injection system technology demonstration was withdrawn from the project due to a combination of perceived risk from the ferry operators and a lower efficiency estimate of system performance during cold-weather conditions.

In-service baseline testing with the vessels' normal No. 2 low sulfur diesel fuel (LSD ~ 500 ppm S) was performed to establish current emissions levels and to gather operational data. The results of the emission control demonstration are:

| Owner | New York Waterway | New York Watertaxi | BillyBey Ferry Company | New York Waterway & BillyBey |
|------------------------------------|-------------------|--------------------------|------------------------|------------------------------|
| Applicable Vessels | 11 | 6 | 12 | 9 |
| Engines | CAT 3406E, 3412E | Detroit Diesel Series 60 | CAT 3406E | CAT 3412C |
| Technology | DOC | DOC | DOC | Re-engine Tier 2 + DOC |
| NOx Reduced, % | -1.06* | -6.28* | -2.38* | 22.7 |
| PM_{2.5} Reduced, % | 41.3 | 32.5 | 60.1 | 84.0 |
| HC Reduced, % | 52.8 | 64.7 | 42.1 | 62.2 |

* Although some changes have been observed in previous installations, the magnitude of the increase in NOx observed in this field study is statistically insignificant with respect to no change in NOx concentrations based on 95% confidence intervals.

This demonstration program is the largest and most extensive onboard emission test program ever performed on a fleet of operating ferries. The results from the demonstrations prove that the use of emissions control technologies on ferries operating in New York harbor is feasible. Properly selected, the devices have the potential to significantly reduce emissions of PM_{2.5}, HC, and CO from the vessel engines. More information on this project is available at: www.northeastdiesel.org/pdf/Technical-NYSERDA.pdf.

3.2 Staten Island Ferry Emissions Reduction Demonstration Project

The Port Authority of New York and New Jersey, in collaboration with the New York City Department of Transportation, has initiated an innovative pilot project to demonstrate emissions reduction technologies on a Staten Island Ferry in 2004. The focus of this project was on NOx reduction and, of the available NOx emission control technologies, SCR was judged to meet the criteria that were set for the project: 1) potential for significant NOx reductions of greater than 70%; 2) an end-of-pipe control system with no intrusion into the main engines; and 3) a proven commercial catalyst technology with more than one vendor to allow for a competitive bid process. SCR, as an aftertreatment device, is completely separate from the engine and is a commercial technology used in several countries, including the U.S. While the focus of the project was on NOx reduction, there was also a desire to reduce particulate matter, volatile organic compound (VOC), and carbon monoxide (CO) emissions as well. Therefore, the *MV Alice Austen* was retrofitted with SCR and DOC systems on its two main CAT 3516A propulsion engines. The Alice Austen Staten Island Ferry vessel was selected for this demonstration project because it is a “relatively” small vessel within the fleet and is equipped with the Caterpillar 3516A four-stroke main engines. In the past, SCR has been successfully installed on several hundred of these specific engines in both marine and power generation applications.

West Virginia University and M.J. Bradley & Associates conducted the emissions test program on the Staten Island Ferry Alice Austen vessel during April 2005 and issued a report summarizing these emission results in August 2006. The emission testing observed on the ferry showed an overall trip reduction of NOx ranging from 68.6% to 81.2% using the installed SCR system. NOx reductions during ferry cruise modes with urea injection operational typically exceeded 94%. The DOC was shown to reduce CO production by 80% to 95%. No clear

conclusions on the effects of the SCR on PM can be made without additional testing because the bulk of the PM was produced during transient engine operation and because the number of PM tests was limited. The Alice Austen has been operating with the SCR since 2005 and there have been no problems with the SCR system. More information on this project is available at: www.mjbradley.com/documents/Austen_Alice_Report_Final_31aug06.pdf.

3.3 *San Francisco Bay Harbor Craft*

The Water Emergency Transit Authority (WETA) ordered four ferries equipped with SCR systems for service in San Francisco Bay. WETA requires cruise emissions from new ferry boats to be 85% below Tier 2 levels in order to mitigate environmental impacts of ferry services. Emissions testing showed the actual emissions to be 96% below Tier 2 levels, and within Tier 4 emission limits. NO_x was reduced by 7% and PM by about 60% compared to engine-out emissions. More information on this is available at: <http://www.efee.com/scr.html>.

3.4 *San Francisco Ferry Retrofit Project*

Under an agreement with the National Park Service, two passenger ferries were retrofitted with SCR systems on the main and generator engines servicing between San Francisco and Alcatraz Island. The first vessel, Alcatraz Flyer has accumulated more than 2800 operating hours since February 2008. The second vessel, Alcatraz Clipper has accumulated 1800 operating hours since September 2008. More information on this is available at: <http://www.efee.com/scr.html>.

3.5 *U.S. Navy Work Boat/Barge*

The California ARB and the U.S. Navy have initiated a demonstration project to reduce diesel emissions from a U.S. Navy work boat/barge. Two 2-stroke DDC 12V-71 engines have been rebuilt with an engine rebuild kit provided by Clean Cam Technology (CCT) Systems. These engines have also been retrofitted with active DPFs and use low sulfur diesel fuel. Preliminary results from emission testing show a 28% reduction in PM and 71% reduction in NO_x emissions were achieved with just the engine modifications; a 76% reduction in PM and small reduction in NO_x emissions with only the active DPF installed; and an 85% reduction in PM and 74% reduction in NO_x emissions with engine modifications plus DPF. Durability and final emission testing was completed in late 2006. More information on this project is available at: www.arb.ca.gov/msprog/offroad/marinevess/presentations/091206/091206tech.pdf.

3.6 *Holland America Seawater Scrubbing Technology Feasibility Study*

Holland America conducted a feasibility study of a new seawater scrubbing technology to reduce emissions from seagoing vessels. In April 2007, seawater scrubber was installed on the ms Zaandam cruise ship and the monitoring of the system began in August 2007. Seawater scrubbing reduces SO₂ emissions from engines by converting it into calcium sulfate. Particulate matter is also reduced by turning it into sludge, keeping it from deposition in the ocean. The stack test results showed that the scrubber removed approximately 75% of SO₂ and 57% of PM generated by the engine as measured by differences in mass of emissions between the inlet and

the outlet of the scrubber. These reductions approximate the use of 0.5% sulfur distillate oil. This \$1.2 million project was funded by a \$300,000 grant from U.S. EPA's West Coast Collaborative and a \$100,000 contribution from the Puget Sound Clean Air Agency. Other project partners include Environment Canada, the Port of Seattle, the Port of Vancouver, and Caterpillar. More information on this project is available at: <http://www.fasterfreightcleanerair.com/pdfs/Presentations/FFCAPNW2008/Dave%20Kircher%20presentation%20FFCA%20PNW.pdf>.

3.7 Marine Experience in Europe and Asia

In addition to these marine vessel demonstration projects, a significant number of large vessels (more than 200), operating primarily in northern Europe, have been equipped with SCR systems over the past ten years. Experience with SCR on these large marine vessels in Europe includes car ferries, passenger ships, cargo transport vessels, and naval vessels. Some ferries operating in Hong Kong have also been equipped with SCR systems. Applications include both new and retrofitted main marine engines and/or auxiliary engines that range from 2000 to 10,000 bhp. These SCR systems have demonstrated 90-99% NO_x reduction, 80-90% hydrocarbon and CO reduction, and 30-40% soot reduction on steady-state operating conditions that match exhaust temperature design windows of the SCR catalysts used in these applications. SCR catalyst design life in these large marine applications can be 40,000 hours or longer depending on total catalyst design volume and the fuel quality used in the application. Separate oxidation catalyst modules can also be included as a part of marine SCR systems. Additional details on the European experience with SCR catalysts on large marine vessels is available in presentations given at the July 26, 2002 ARB Maritime Air Quality Technical Working Group Meeting (see: arb.ca.gov/msprog/offroad/marinevess/presentations.htm#091906).

There have been some limited applications of DOCs on large marine engines including some luxury yachts and passenger ferries operating in Hong Kong. Burner-based, active DPF designs similar to those used in Swiss locomotive applications have also been installed on sight-seeing ships operating on some of the large lakes in Switzerland for significant reductions in PM emissions.

4.0 FUNDED PROJECTS

4.1 American Reinvestment and Recovery Act of 2009 (ARRA)

In April 2009, the U.S. EPA began awarding \$88 million from the federal stimulus package Diesel Emission Reduction Act (DERA) funds to states for programs to clean up or retrofit diesel engines. Under the American Reinvestment and Recovery Act (ARRA) of 2009 state clean diesel funding program, all 50 states and the District of Columbia received \$1.73 million to reduce emissions from diesel vehicles. The following projects will receive funding to reduce diesel emissions from locomotive and marine diesel engines:

- California Air Resources Board received \$8,888,888 in funding to repower eight switch yard locomotives that operate with new Tier 3 engines. The affected locomotives are owned by Union Pacific Railroad and BNSF Railway and operate in the Southern California region.

- The City of Los Angeles Harbor Department received \$1,991,750 in funding to replace, repower, and/or retrofit a total of 27 pieces of equipment, including harbor craft, currently in operation at the port. The emission reductions achieved from this project will improve air quality and health in the surrounding areas.
- Duke Energy, Mecklenburg County, received \$79,882 in funding to repower a switcher locomotive
- Maine will fund the state’s Clean Diesel Program, specifically to retrofit transit buses and refuse trucks, as well as repower and retrofit port cargo handling equipment. The funds will provide shore power to reduce emissions on the waterfront at Fore River dock. The funding will also assist efforts of the Maine Clean School Bus Program and will allow Maine Department of Environmental Protection to establish the first statewide Clean Marine Engine Program in the region to replace dirty marine engines.
- Northeast States for Coordinated Air Use Management received \$2.7 million for projects in Maine, New Hampshire, and Vermont to replace old diesel engines on five ferries and three tugboats. In New Haven, Connecticut, it will replace a diesel engine on a switcher locomotive.
- Port Authority of New York and New Jersey received \$9.8 million to replace old trucks with newer, cleaner models and reduce diesel emissions from idling cruise ships.

5.0 RETROFIT VERIFICATIONS FOR MARINE ENGINES

In its National Clean Diesel Campaign’s Emerging Technology List, EPA lists several marine emissions upgrade kits that is expected to reduce diesel emissions from marine engines. The Emerging Technology List is intended to provide guidance in selecting a technology for the Clean Diesel Emerging Technologies Program’s Request for Proposals. A technology may stay on the Emerging Technology List for one year from the effective date. During that year, the manufacturer will seek full verification. More information on this list is available at: <http://www.epa.gov/diesel/prgemerglist.htm>.

EPA Emerging Technologies List: Marine Application

| Technology | Reduction | | | | Effective Date |
|------------------------------|-----------|-----|-------|-----|-----------------|
| | PM | NOx | HC | CO | |
| Marine Emissions Upgrade Kit | 25 | N/A | N/A | N/A | July 10, 2008 |
| Marine Emissions Upgrade Kit | 25 | N/A | 21-29 | N/A | July 10, 2008 |
| Marine Emissions Upgrade Kit | 25 | N/A | 41-49 | N/A | July 10, 2008 |
| DOC Kit | 25 | 0 | 25 | 70 | October 6, 2008 |

The California ARB has verified an active partial DPF for marine harbor craft engine. The DPF is verified to reduce PM by 50% (Level 2). More information on this marine retrofit technology is available at: <http://www.arb.ca.gov/diesel/verdev/vt/cvt.htm>.

6.0 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 ultra-low sulfur diesel (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 NO_x emissions, such as lean NO_x 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 NO_x 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.