Retrofitting Compact SCR™ and Diesel Particulate Filters to a Passenger Ferry

April 17, 2010

Submitted to:
Innovative Clean Air Technologies Program
California Air Resources Board

EF & EE
ENGINE, FUEL, AND EMISSIONS ENGINEERING, INCORPORATED

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Submitted to
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Research Division
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Disclaimer

ACKNOWLEDGEMENTS

This report was submitted under Innovative Clean Air Technologies grant number 06-04 from the California Air Resources Board.

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1. ABSTRACT

An emission control system combining diesel particulate filters (DPF) with selective catalytic reduction (SCR) has been developed for retrofit to diesel engines in harborcraft. The SCR system builds on the existing Compact SCR™ technology developed for harborcraft 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 harborcraft emission regulations. The same is not true for the older Tier 0 diesel engines found in many California harborcraft, due to the much higher PM emissions 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. The main propulsion engines on this vessel are two Caterpillar 3412 diesels rated at 520 horsepower each, while the generator engines are two Caterpillar D377s. The generators are rated at 50 kW each. To date, 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* is presently out of service, undergoing repairs to her marine gearing, and EF&EE is 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, is expected to go into operation when the vessel returns to service about the end of April.

Preliminary emission testing on the Starboard Main engine showed NOx control efficiency of 85 to 90%, depending on load. PM efficiency was 78% at 50% load, but dropped to less than 50% at the 75% and full-load conditions. This is ascribed to inadequate passive regeneration clogging the DPF with soot, causing the DPF bypass valve to open under high load. The revised active regeneration system is expected to eliminate this problem.

2. INTRODUCTION

The Air Resources Board (ARB) has identified diesel particulate matter as a toxic air contaminant, responsible for about 70% of all cancer risk due to air pollution. In response, ARB has adopted its Diesel Risk Reduction Program, which will ultimately require most diesel engines used in California to be equipped with DPFs or other particulate control devices. Diesel particulate emissions are also an important contributor to ambient PM2.5 levels, and diesel NOx emissions are a significant part of the ozone problem in many California air basins.

Harborcraft, tugboats, ferryboats, and other commercial diesel boats account for about 23 tons of NOx and 1.2 tons of diesel PM emissions per day in California – about one percent of total mobile source emissions of each of these pollutants. In the future, increasing marine freight traffic – especially in the Ports of Los Angeles and Long Beach – and plans for a major expansion of ferry service in San Francisco Bay will tend to increase the share of marine diesel emissions in the statewide emission inventory.

As other diesel mobile sources have come under control, emissions from harborcraft have begun to receive more attention. In 2007, the Air Resources Board adopted a new harborcraft rule (17 CCR 93118.5). This rule makes engine replacement and/or emission control retrofits mandatory for nearly all commercial boats operating in California. The phase-in schedule specified by the rule begins by replacing the oldest engines in 2008, with Tier 3 engines beginning in 2013, and/or with level 3 retrofit particulate control systems beginning in 2016.

Commercial marine engines have extremely long useful lives, and are often prohibitively expensive to replace. Thus, a retrofit system that would allow these engines to meet the forthcoming regulations will be commercially attractive to many vessel operators. By reducing the costs to vessel operators, it would also improve the cost-effectiveness of the proposed regulations, and potentially enable them to go into effect more rapidly and with fewer "hardship" exemptions. Finally, a retrofit system that includes selective catalytic reduction can achieve lower NOx emissions than would be required under the draft regulations, potentially qualifying it for partial funding under the Carl Moyer Program.

Engine, Fuel, and Emissions Engineering, Inc. (EF&EE) has pioneered the application of selective catalytic reduction (SCR) systems to harborcraft. Eight vessels equipped with SCR systems are presently in operation in North America; seven of these are equipped with Compact SCR™ systems from EF&EE. The experience with and present status of Compact SCR™ technology are described in Chapter 3 of this report.

For modern diesel engines in marine service, retrofitting with Compact SCR™ technology typically reduces NOx emissions by 95% or more, PM emissions by 40 to 60%, and CO and VOC emissions by 70 to 90%. Most marine engines certified to EPA Tier 2 emission standards can achieve EPA Tier 4 levels with Compact SCR™. Older-technology diesels tend to have much higher PM emissions, however, so that the 40 to 60% reduction in PM due to the Compact SCR™ system may not be enough to bring them into compliance with the ARB rules. For these older engines, the Compact SCR™ system needs to be supplemented with a diesel particulate filter (DPF).

In 2006, EF&EE applied for ARB funding through the Innovative Clean Air Technology (ICAT) Grant Program; with the goal of EF&EE's of developing and demonstrating an emission control system that would Compact SCR™ and DPF technologies, and that would be suitable for retrofit to existing harborcraft equipped with older "Tier 0" engines without emission controls. The grant agreement was signed in early 2007. After the planned host organization withdrew, Blue and Gold Fleet of San Francisco agreed to host the demonstration. Installation of the demonstration system on M/V *Royal Star*, an 800 passenger ferry belonging to Blue and Gold Fleet, began in May, 2009. The demonstration program is ongoing, and ARB verification of the Compact SCR+DPF technology is expected before the end of 2010.

Once successfully verified and commercialized, these Compact SCR+DPF systems are expected to provide substantial economic benefits to California. The following are some of the key benefits:

(1) Helping to relieve the constraints on port traffic posed by air pollution limits, thus making possible increased cargo traffic, economic growth, and employment;

(2) Reducing pollutant emissions produced in the course of dredging, drilling, and similar operations, and thus the costs of pollutant mitigation measures. This, in turn, will reduce the overall costs of capital improvements such as harbor dredging and construction of new marine terminals, thus making these investments more attractive;

(3) Reducing costs of emissions compliance, and thus improving the competitiveness of California ports compared to other west coast port options;

(4) Reducing the health costs imposed on workers and the general public by exposure to diesel pollutant emissions;

(5) Direct employment for technicians and engineers and increased business for subcontractors in building and installing the retrofit systems, resulting in increased income and employment taxes to the State.

At present, the cost-effectiveness guideline for the Carl Moyer Program is 14,300 per ton of combined emissions, calculated as the sum of NOx + HC + (20 x PM). This represents a rough estimate of the marginal cost to California citizens to achieve further emission reductions through regulation. Installing Compact SCR on a typical vessel will reduce combined emissions by about 10 to 20 tons per year, at a cost of about $2,000 to $3,000 per ton. To conform to federal air quality standards, these emission reductions would otherwise have to be achieved by other regulatory means, at a cost of around $14,300 per ton or more. Thus, each ton of emissions reduced by Compact SCR+DPF systems will result in a saving to California society of about ($14,300 - $2,500), or about $11,800. For a typical harborcraft installation, this will amount to about 100,000 to 200,000 dollars per year.

3. COMPACT SCR™ TECHNOLOGY

This demonstration project combines EF&EE's already-developed Compact SCR™ technology with diesel particulate filters. This chapter gives an explanation and development history of the Compact SCR™ technology.

3.1 HOW COMPACT SCR™ WORKS

The Compact SCR system includes an exhaust catalyst assembly, similar to the catalytic converter in a car but much larger. Like the catalytic converter in a car, the Compact SCR catalyst works to oxidize (burn) the unburned hydrocarbons, CO, and oil droplets that are emitted from the engine. In a gasoline car, the three-way catalytic converter also works to reduce NOx emissions by reacting the NOx molecules with some of the hydrocarbons and CO to produce harmless nitrogen gas, carbon dioxide, and water. However, this reaction can only happen if there is very little oxygen present in the exhaust.

Diesel engines always run with excess air, so there is always a lot of oxygen and very little HC or CO present in the exhaust. For this reason, they can't use three-way catalysts to control their NOx emissions. Instead, the Compact SCR catalyst destroys NOx emissions by reacting the NOx molecules selectively with molecules of ammonia (NH_3). This reaction converts both the NOx and the ammonia to harmless nitrogen gas (N_2) and water (H_2O).

Ammonia isn't normally present in diesel exhaust, so it has to be supplied by the Compact SCR system. Pure ammonia is a poisonous, caustic, foul-smelling gas – not something you'd want to keep around. For that reason, the Compact SCR system supplies a related chemical instead. That related chemical is urea [$(NH_2)_2CO$] dissolved in water.

Unlike ammonia, urea and urea-water solutions are non-poisonous and safe to handle. When injected into the hot exhaust, however, each urea molecule decomposes and reacts with water to form two ammonia molecules and one molecule of CO_2. The ammonia molecules then react with any NOx molecules present in a reaction facilitated by the SCR catalyst, thus destroying both the ammonia and the NOx. To prevent any ammonia "slip" (leftover ammonia) from escaping, a narrow layer of finely-dispersed platinum catalyst is placed at the end of the SCR modules to burn any remaining ammonia to nitrogen and water.

Figure 1 is a diagram showing how the urea injection system works. Liquid urea solution is kept in a tank on-board. The metering pump draws the urea solution from the tank, and pushes it through a paddlewheel flow sensor. To prime the pump, or when urea injection is not called for, the urea diverter valve is kept closed so that the urea returns to the tank.

When the control system calls for urea injection, the urea diverter valve opens, allowing the liquid to pass through and mix with compressed air from the vessel's air compressor system. The mixture of urea solution and compressed air is then atomized as it sprays out of the injection nozzle into the exhaust stream.

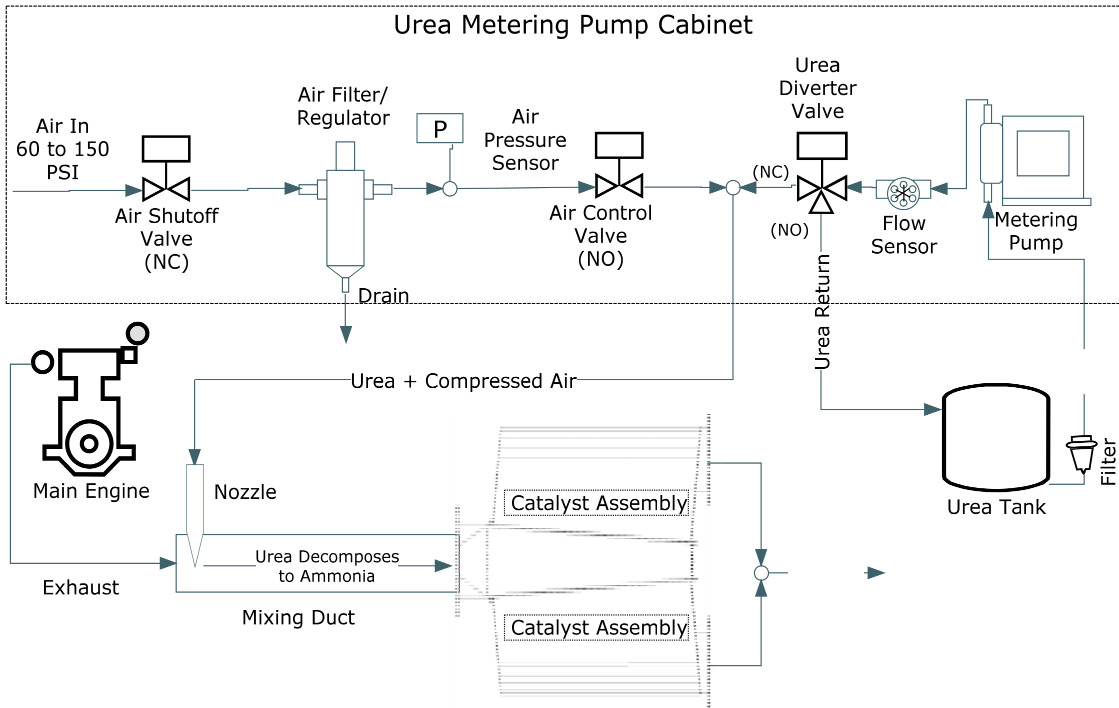


Figure 1: Diagram of the Compact SCR urea injection system

The SCR control system estimates the temperature of the exhaust catalyst by measuring the temperature of the exhaust going in, and allowing for the time lag as the catalyst temperature responds to the exhaust temperature. The SCR reactions require an exhaust temperature of at least 200 ^{o}C. If the estimated catalyst temperature is too low, the control system will not command urea injection.

If too little urea is injected, some of the NOx will escape unreacted, while injecting too much urea is wasteful, and can lead to ammonia slip. The Compact SCR control system is programmed to adjust the urea flow rate from the metering pump to match the rate of NOx emissions from the engine. The rate of NOx emissions from the main engines is calculated from the engine RPM, along with the results of emission measurements carried out during vessel commissioning.

3.2 Development History

In 2005, EF&EE entered into discussions with a Detroit Diesel / MTU engine distributor, Pacific Power Products Company (PPPC), regarding the supply of SCR systems for two new vessels for the Water Transit Authority (WTA) of San Francisco Bay. The WTA (now the Water Emergency Transportation Authority, WETA) is the regional government agency responsible for coordinating ferry service on San Francisco Bay. The bid specifications development by the WTA required the main engines in the new ferries to reach emission levels 85% below EPA Tier 2 standards. This requirement could only be met using natural gas fuel or SCR.

In response to this challenge, EF&EE developed a small-scale prototype of what is now our Compact SCR™ technology, and successfully tested it on PPPC's dynamometer in March, 2006. The winning bid for the ferry contract incorporated MTU engines supplied through PPPC and fitted with EF&EE's Compact SCR™ system. After delays in contract award due to litigation, EF&EE received the purchase order for four Compact SCR™ systems for the WTA ferries in March, 2007. The first complete system was tested on PPPC's dynamometer in January 2008, with emissions 95% below Tier 2. Sea trials of the first boat, M/V *Gemini*, were held in November, 2008, showing emissions 97% below Tier 2.

At *Gemini*'s public debut in December, 2008, she was called "the most environmentally friendly ferry in North America", and "a benchmark for the world". Since January, 2009, M/V *Gemini* has operated in regular ferry service between Tiburon and San Francisco. Follow up testing in August, 2009, showed that the Compact SCR™ systems were still reducing emissions 90-95% below Tier 2 levels after 750 hours of operation.

Figure 2: Artist's depiction of M/V Gemini in San Francisco Bay

The second of the two original WTA boats, M/V *Pisces*, also demonstrated emissions 97% below Tier 2 in sea trials, and entered service in April, 2009. The WTA subsequently ordered two more ferries equipped with the same engines and SCR systems. The first of these, M/V *Scorpio*, entered service in December, 2009, and the last, M/V *Taurus* completed sea trials in April, 2010. Emission tests were conducted on both vessels during sea trials, and showed emission levels 96 to 98% below Tier 2. Emission data for M/V *Scorpio* at the 85% load point used for acceptance testing are shown in Table 1. Figure 3 plots the NOx emissions from her main engines with and without the Compact SCR system in operation.

Another Compact SCR™ customer has been Hornblower Cruises and Events in San Francisco, CA. Hornblower won the U.S. National Park Service ferry franchise for Alcatraz Island in 2006, in part by promising to implement state-of-the-art emission controls on its ferry fleet. To fulfill this promise, two Alcatraz ferryboats were repowered with Detroit Diesel main engines, new generating sets, and EF&EE Compact SCR™ systems on both the main and generator engines. The first of these vessels, M/V *Alcatraz Flyer*, returned to service in February, 2008, and has accumulated more than 3000 main engine hours to date. M/V *Alcatraz Clipper* returned to service in September, 2008, and has accumulated more than 1800 engine hours.

Table 1: Emissions from M/V *Scorpio* with Compact SCR™ at 85% load cruise

Test	g/kWh			g/kg fuel			g/hr		
File	PM	CO	NOx	PM	CO	NOx	PM	CO	NOx
STARBOARD ENGINE									
R3T1987	-	0.12	0.25	-	0.6	1.2	-	75.9	157.3
R3T1988	-	0.06	0.24	-	0.3	1.2	-	40.3	152.6
R3T1990	0.023	0.08	0.24	0.11	0.4	1.1	14.7	52.6	148.1
Average	0.023	0.09	0.24	0.11	0.4	1.2	14.7	56.3	152.7
C.V.	-	32%	3%	-	32%	3%	-	32%	3%
PORT ENGINE									
R3T1993	0.031	0.13	0.27	0.15	0.6	1.3	19.7	85.9	170.3
R3T1994	0.024	0.04	0.29	0.12	0.2	1.4	15.5	24.8	188.4
R3T1995	0.023	0.07	0.28	0.11	0.3	1.4	14.9	44.5	180.1
Average	0.026	0.08	0.28	0.13	0.4	1.3	16.7	51.7	179.6
C.V.	16%	60%	5%	16%	60%	5%	16%	60%	5%

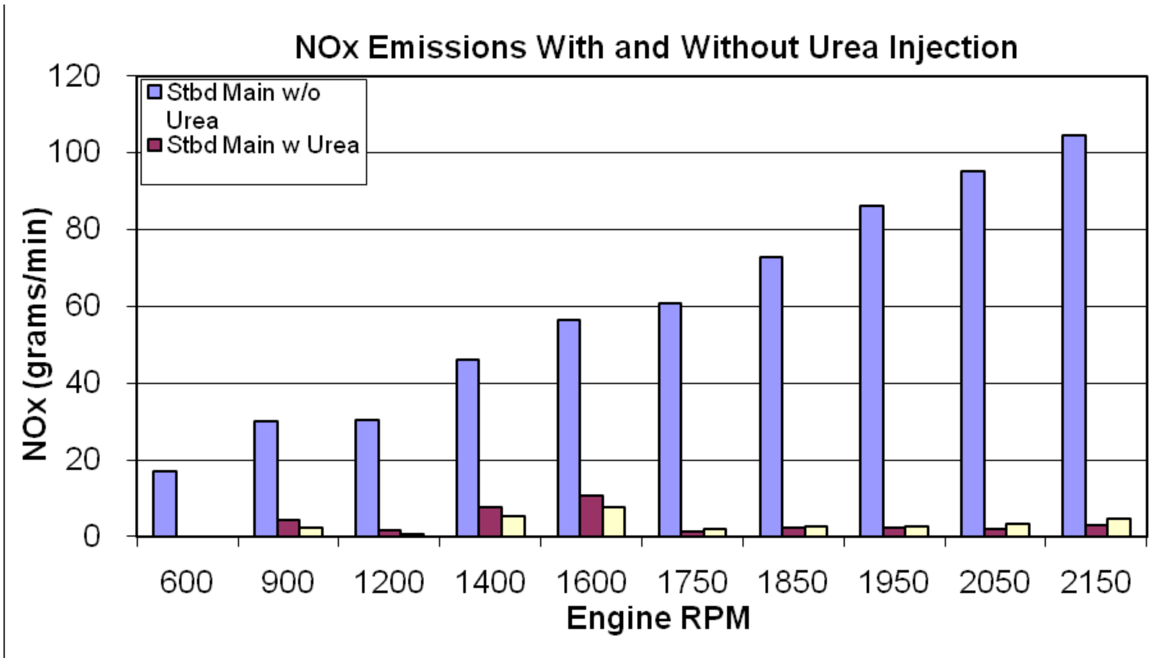


Figure 3: NOx emissions from M/V *Scorpio* with and without Compact SCR™ in operation

Although ordered later than the WTA ferries, the Compact SCR systems on *Alcatraz Flyer* were the first to go into service. The experience gained from this early implementation of Compact SCR™ led to a number of design and software changes in the later systems.

In addition to the 18 Compact SCR™ systems presently installed in ferries, EF&EE has installed three Compact SCR™ systems in stationary generating systems, and one in a passenger locomotive. One system installed in a stationary generator has accumulated more than 6000 operating hours in the last year.

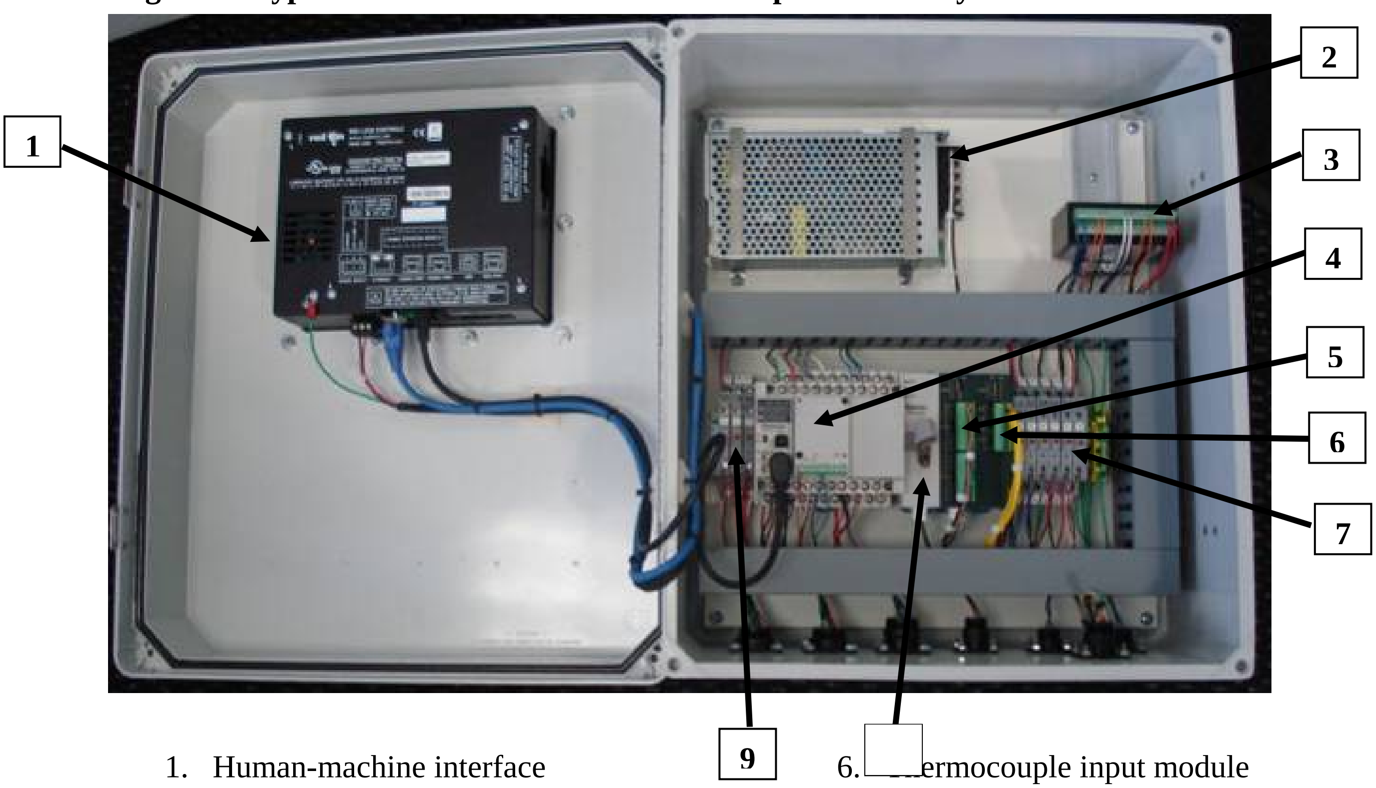
3.3 Control and Urea Metering System

The urea metering and control system is a key element of Compact SCR technology. These systems all follow a common pattern, in which a single PLC-based control unit manages up to four urea metering pump assemblies. The metering pump assemblies mix urea solution at a controlled rate with compressed air This mixture then expands into the exhaust through an atomizing nozzle. The rate of urea mixing is determined by the central control unit as a pre-calibrated function of some proxy for engine load. For marine propulsion engines driving fixed-pitch propellers, the engine RPM provides a suitable proxy for engine load. For generating sets, the generator power output provides serves to indicate the engine load.

3.3.1 Central control unit

The central control unit contains the PLC, signal conditioning, power distribution, and the main human-machine interface (HMI) for the Compact SCR system. The interior is pictured in the photo below, with callouts to identify the major components.

Figure 4: Typical central control unit for a Compact SCR™ system



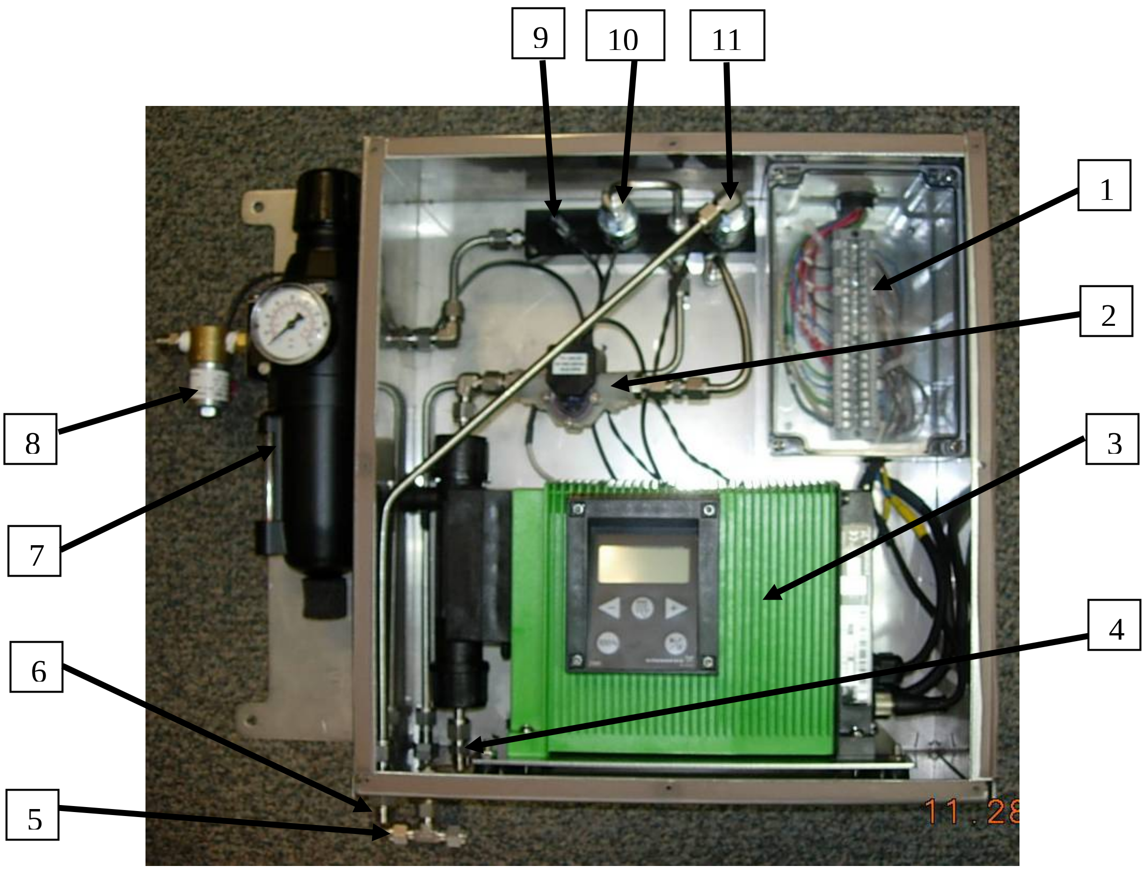
1. Human-machine interface
2. DC power supply
3. 8 channel optical isolator
4. PLC with voltage input cassette
5. Analog (current) input module
6. ermocouple input module
7. 24 volt DC fuse holders
8. Module-to-PLC adapter
9. 120 volt AC fuse holders

The primary means of operator interaction with the Compact SCR control and metering system is through a touchscreen human-machine interface (HMI) located on the front panel of the central control unit. In marine installations, a second, repeater HMI is normally provided on the bridge of the vessel. The controller can also be accessed from remote locations via the Internet.

3.3.2 Urea Metering Pump Asssembly

The urea metering pumps are contained in stainless-steel cabinets mounted on the wall of each engine room. Each cabinet also contains the sensors and solenoid valves used to control urea injection. External connections include a CPC for the multiconductor cable to the central control unit and ¼ inch compression fittings for urea supply, urea return (to the tank), compressed air supply, and the urea/compressed air mixture to the injection nozzle. The photo below shows the metering pump cabinet with the front panel removed, with callouts to identify the major components. A complete parts list is given in the table that follows.

Figure 5: Typical urea metering pump assembly



1. Electrical terminal enclosure
2. Urea flow sensor
3. Urea metering pump
4. Urea inlet
5. Urea-air injection line
6. Urea return
7. Compressed air filter/regulator
8. Compressed air shutoff valve
9. Compressed air pressure sensor
10. Compressed air control valve
11. Urea diverter valve

The electrical connections are located inside a NEMA IV terminal enclosure to product them from possible urea leaks.

3.3.3 System Operating States And Fault Codes

The present operating state of each SCR system is shown in the Status indicators on the Main Screen. These states can be divided into those that indicate normal operation, and fault conditions. The fault conditions are FLT1 through FLT7, and are each displayed with a red background. In addition to the documentation here, touching the status indicator on the Main Screen will bring up a pop-up window to explain the status code that is being displayed.

Normal Operation

The normal operating conditions are WAIT, CHEK, STBY, INJT, OUT, and MANL.

WAIT is displayed immediately after system power-up or reset, until the compressed-air pressure sensor indicates that the air pressure has reached a normal level. (Note: loss of compressed air pressure after the initial startup checks results in FLT1 instead).

CHEK is displayed while the system is performing start-up checks for leaking or clogged urea injection lines. This involves closing the air shutoff valve, and measuring the time required for the air pressure to bleed out through the injection nozzle.

STBY is displayed after the system passes its startup-checks, when the system is ready but the present exhaust temperature or engine RPM do not call for urea injection.

INJT is displayed after the system passes its startup checks, when the system is injecting urea under automatic control.

OUT is displayed if the urea tank OUT level switch is open, indicating that the urea level is too low to continue injecting.

MANL is displayed if the system is in manual operating mode. In this mode, the operator determines the position of the solenoid valves and the urea injection rate commanded. To resume automatic operation, push the MANL/AUTO indicator on the Port or Starboard metering system screens. To change the MANL/AUTO mode requires that the user be logged-in, and that he or she have been assigned the "Maintenance" right in the security management software.

Fault Codes

There are seven fault codes: FLT1 through FLT7. Urea injection is cut off whenever one of these indicators is displayed. Once the fault is cleared, the system will reset – first going through its self-checks, then (if those are successful) entering normal operation.

FLT1 indicates that the compressed air pressure fell below the minimum operating level of 30 PSIG. This fault will clear when the compressed air pressure exceeds 35 PSIG. Possible causes include: air compressor turned off, compressed air supply valves shut, compressed air shutoff valve malfunction, and blockage of the air supply plumbing with urea crystals.

FLT2 indicates that the injection line or injection nozzle are clogged (i.e. it takes more than 30 seconds for air pressure to bleed down after closing the air shutoff valve). This condition is only detected during the initial startup checks. It is usually due to blockage of the urea injection line with dried urea crystals, and can usually be cleared by closing the air control valve (to keep urea out of the air system) and pumping a modest amount of urea solution into the injection line to dissolve the crystals. When this condition is detected, the control system will periodically attempt to clear the blockage in this way, then reset to go through the start-up checks again.

FLT3 indicates a pressure leak in the urea injection system (i.e. it takes less than 2 seconds for air pressure to bleed down after closing the shutoff valve).

FLT4 indicates that the exhaust temperature reported by the sensor is below 0 ^{o}C or above 550 ^{o}C, generally indicating a fault in the thermocouple, its wiring, or the PLC thermocouple module. A temperature indication of 800 ^{o}C signals a broken thermocouple. This fault will clear if the reported temperature falls between 0 and 500 ^{o}C.

FLT5 indicates either that the exhaust backpressure is above the safe operating range for the engine, or that there is a backpressure sensor fault.

FLT6 indicates that the internal alarm relay on the urea metering pump has opened,, or that the wiring to that relay has become disconnected.

FLT7 indicates that the urea flow sensor is not reporting adequate urea flow, even though the metering pump is pumping. This may be due to blockage of the urea feed line or filters, sticking ball valves in the metering pump (typically due to urea drying in the pump), or a problem with the flow sensor.

4. DEVELOPMENT OF COMPACT SCR+DPF™ TECHNOLOGY

4.1 DESIGN ISSUES

As noted in the Introduction, 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. To satisfy the Coast Guard requirements involves two principal design challenges. First, it is essential to ensure that that the emission control system cannot 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 to 500 ^{o}C. Coast Guard regulations require that the exhaust system be fully insulated for fire and personnel safety. Second, it is essential to ensure that any emission control system failure cannot 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. Thus, 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 are sized for truck engines, this means that multiple parallel DPF/catalyst elements are required. It is also essential to ensure that the DPF system cannot become blocked to such an extent that the backpressure could damage the engine.

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 ^{o}C, as it could during an assisted regeneration.

This emission control system is intended for use with older engines having relatively high PM emissions. Thus, 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, we elected to use multiple DPFs for each engine, and to regenerate each DPF separately. Thus, the hot exhaust from the DPF undergoing regeneration would be diluted by the cooler exhaust passing through at least one other DPF. This led us 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.

4.2 DPF SELECTION

Substantial effort was spent on selecting the appropriate DPF. Our initial plan was to use a silicon carbide wall-flow monoliths coated with precious-metal catalyst to aid in regeneration. In 2008, we identified an alternative technology that appeared very promising – a fibrous ceramic paper from Industrial Ceramics, Inc. that could be pleated to form filter elements. This fabric material offered the potential for high filtration efficiency with lower mass (and thus less energy required for regeneration) and less backpressure than the silicon carbide monoliths.

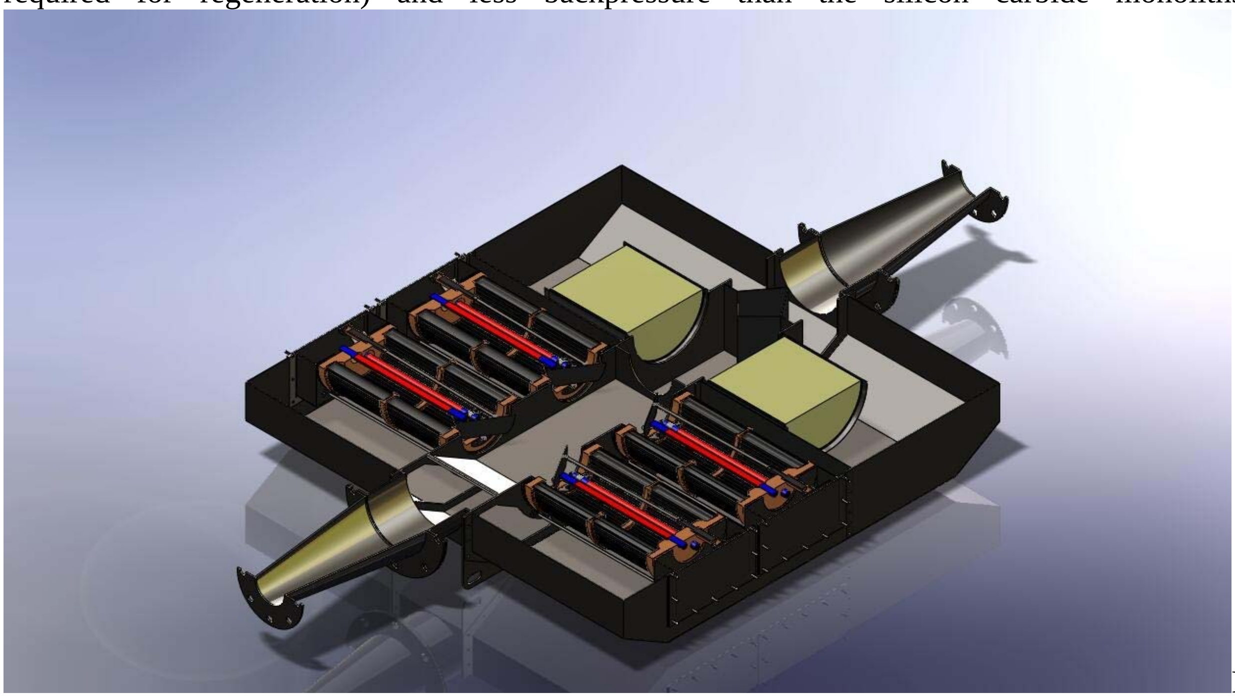


Figure 6 shows a sectional view of a combined DPF and SCR catalyst assembly incorporating these elements. Although the technology appears promising, it was ultimately necessary to suspend further development when the supplier proved unable to provide the DPF materials in time to meet the project schedule.

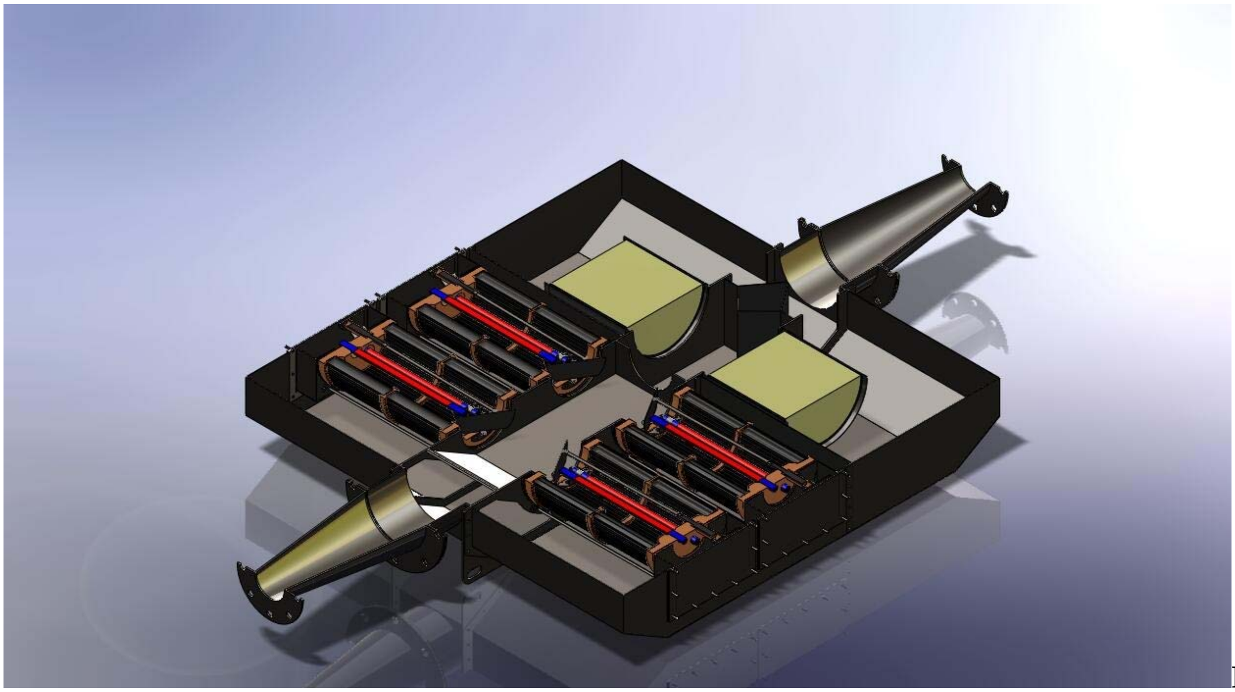


Figure 6: Combined DPF and SCR catalyst housing incorporating Industrial Ceramic filter elements

Having suspended development of the ceramic paper DPFs, the emphasis shifted to the silicon carbide monoliths. Working in cooperation 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. Figure 7 is a plot showing the rate of NO_2 emissions from EF&EE's diesel generator with the DPF alone, the SCR catalyst alone, both together, and with no aftertreatment. While the SCR catalyst reduces the rate of NO_2 emissions, the increase due to the DPF more than offsets this.

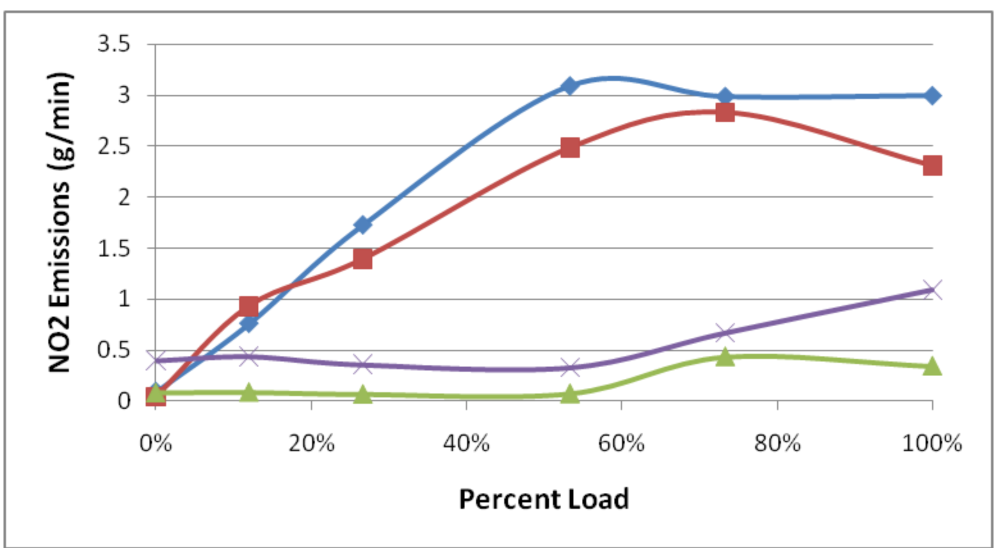


Figure 7: NO_2 emissions vs generator load with DPF and SCR catalysts

The DPF supplier was able to offer us two catalyst formulations with less tendency to convert NO to NO_2. The first of these, called NO2P by the supplier, used a reduced 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, this second formulation was also less expensive, but also less effective in promoting DPF regeneration.

Since 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 therefore used on the DPFs for the Port main engine and generating set, while the NO2X formulation was used in those for the Starboard.

4.3 DPF REGENERATION ISSUES

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. Thus, it was expected that DPF regeneration on these engines would nearly always require active intervention.

Most DPF retrofit systems used on trucks rely for regeneration on diesel fuel burners or catalytic combustion of diesel fuel in the exhaust. 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 DPFs, electric resistance heating has the extra advantage that it adds to the load on the generator, thus increasing the engine-out exhaust temperature as well.

Our 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 we determined that the grade of silicon carbide used in our prototypes became conductive at temperatures around 300 ^{o}C – thus 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.

The resulting design of the DPF assemblies for the main engines is shown in Figure 8 and Figure 9. In the latter figure, exhaust enters the assembly from the left into the central plenum of the DPF assembly. There it divides, with half flowing upward through the two silicon carbide wall-flow monoliths (dark gray) connected to the upper side of the plenum, and the other half flowing through the two similar monoliths connected to the lower side. Each of the four monoliths has its own 5 kW electric heating element located immediately in front of it where it joins the plenum.

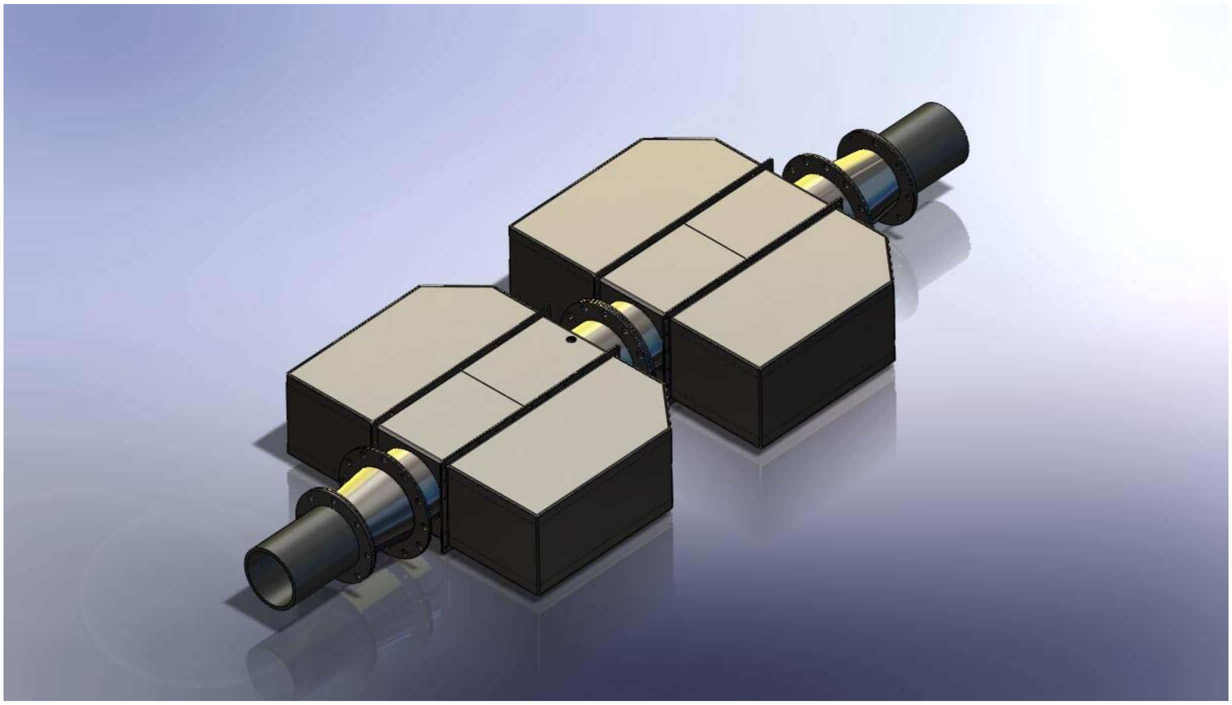


Figure 8: Main engine DPF and SCR catalyst assemblies

After passing through wall-flow monoliths, the two exhaust streams are collected under the covers, then recombined at the exit to the DPF assembly. The urea injection for the SCR system takes place at this point. The combined exhaust stream then passes into the SCR catalyst assembly, where the same flow pattern is repeated.

Given the lesser exhaust flow rate from the generators, it was practical to design the DPF and SCR catalyst supports as a single assembly, rather than two. The result is rendered in Figure 10, and a cross-sectional view is given in Figure 11. The exhaust would enter from the left of Figure 11 and pass through one of the two DPF monoliths. Urea is injected into the plenum space behind the two monoliths. From that space, the exhaust flows through a port (designed to improve mixing) and then through the single SCR catalyst element.

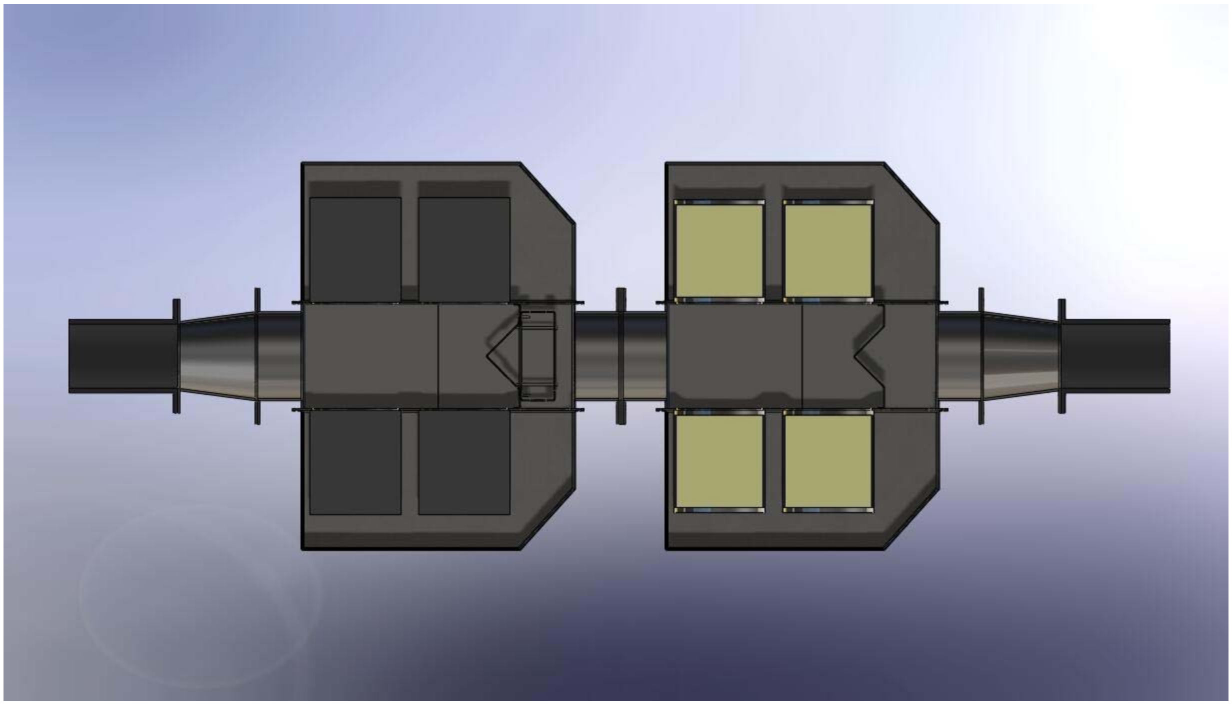


Figure 9: Cross section of the main engine DPF and SCR catalyst assemblies

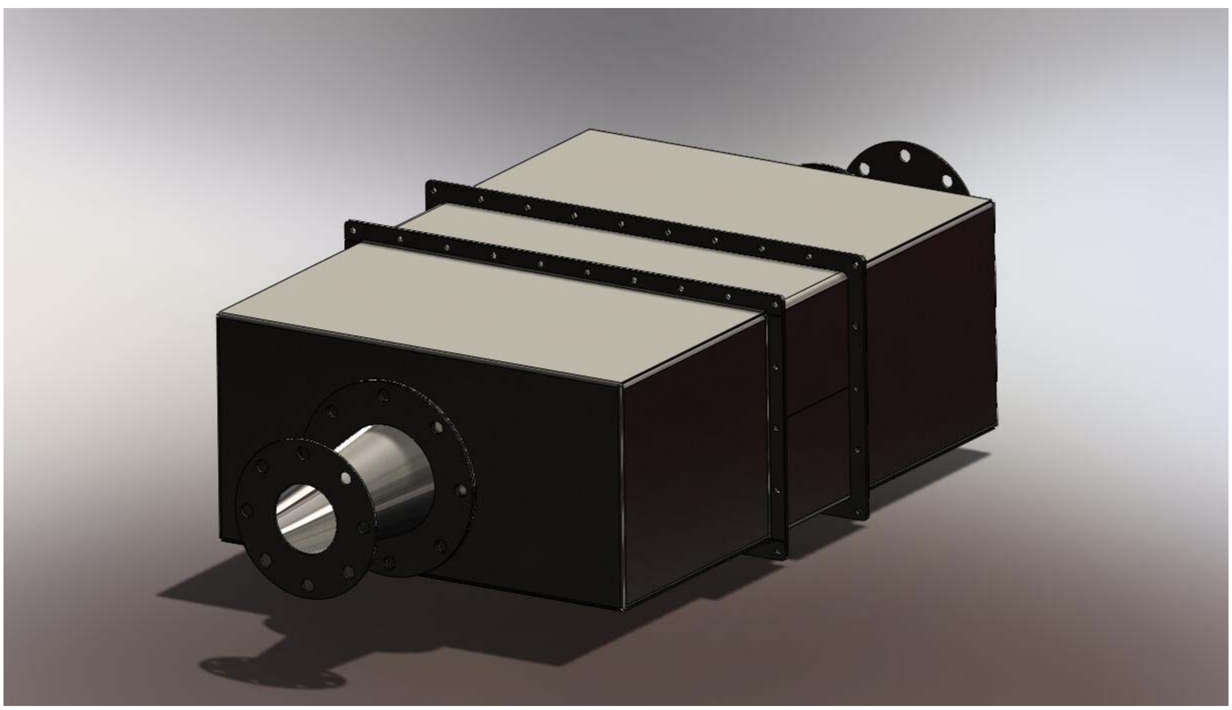


Figure 10: One of the combined DPF and SCR catalyst assemblies for the generator engines

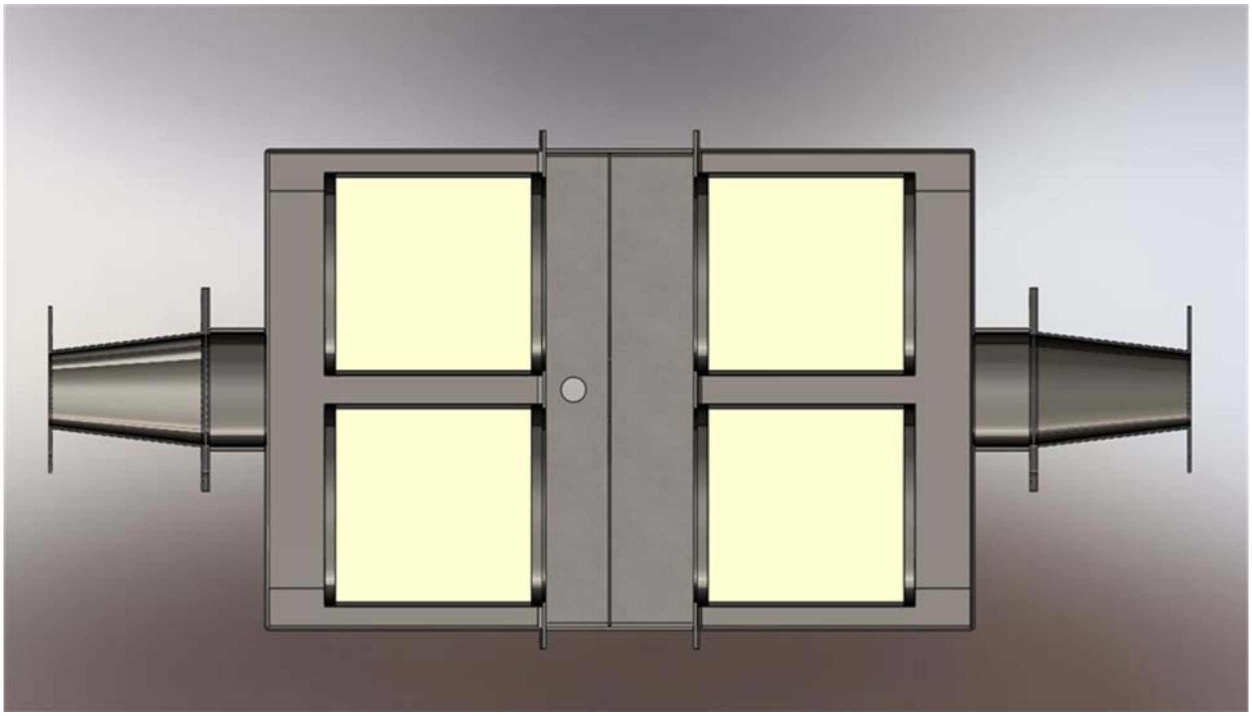


Figure 11: Cross section of the combined DPF and SCR catalyst assembly for the generator engine

Figure 12: SCR and DPF assemblies for the Starboard main engine, *in situ*, viewed from the aft (downstream) end with lagging partially removed

Figure 13: Combined DPF and SCR catalyst assembly for the Starboard generator, in situ with lagging partially removed

4.4 UREA METERING, MONITORING, AND CONTROL

As installed on M/V *Royal Star*, urea metering, monitoring and control system comprises a central control unit and four urea metering pump assemblies similar to those described in Section 3.3. In addition, the central control unit activates the relays that switch the 208 volt electrical current to each of the electric heaters used to regenerate the DPFs.

Inputs to the central control unit include:

- Tachometer pulses from each of the two main engines;
- Outputs from two three-phase power sensors, one connected to the output of each generator;
- Thermocouples located in the exhaust upstream of each DPF assembly and downstream of each SCR catalyst assembly;
- Exhaust backpressure sensors located upstream from each DPF assembly;
- Compressed air pressure sensors and urea flow sensors in each metering pump assembly;
- Level switches corresponding to the “low” and “empty” positions in the urea solution tank; and

- An AC current transducer configured to measure the actual current flow in the DPF regeneration circuit.

In the future, we expect to add exhaust NOx sensors as well.

Control outputs from the central control unit are:

- Activation signals for the air shutoff, air control, and urea diverter valves in each of the four metering pump cabinets;
- A pulse frequency signal controlling the urea flow rate from each of the four metering pumps;
- The activation signal for the solid-state relay that controls the flow of electric current in the DPF regeneration circuit;
- Activation signals for each of the twelve relays that switch the DPF regeneration circuit to the heater elements for each of the twelve DPF modules.

5. OPERATING EXPERIENCE WITH THE COMPACT SCR+DPF™ SYSTEM

Except for the DPF modules and regeneration system, the Compact SCR+DPF system was installed in M/V *Royal Star* during 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 of that year, while those for the generators were installed in April, 2010.

The Compact SCR™ systems on *Royal Star* were active beginning in early September, 2009. Figure 14 plots the cumulative operating hours for the Starboard main engine, as well as the estimated engine-out and catalyst out NOx emissions. As this figure shows, 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 shows that the urea injector was plugged, probably due to urea solution drying out in the line. EF&EE is now in the process of restoring the Compact SCR™ system to full operation.

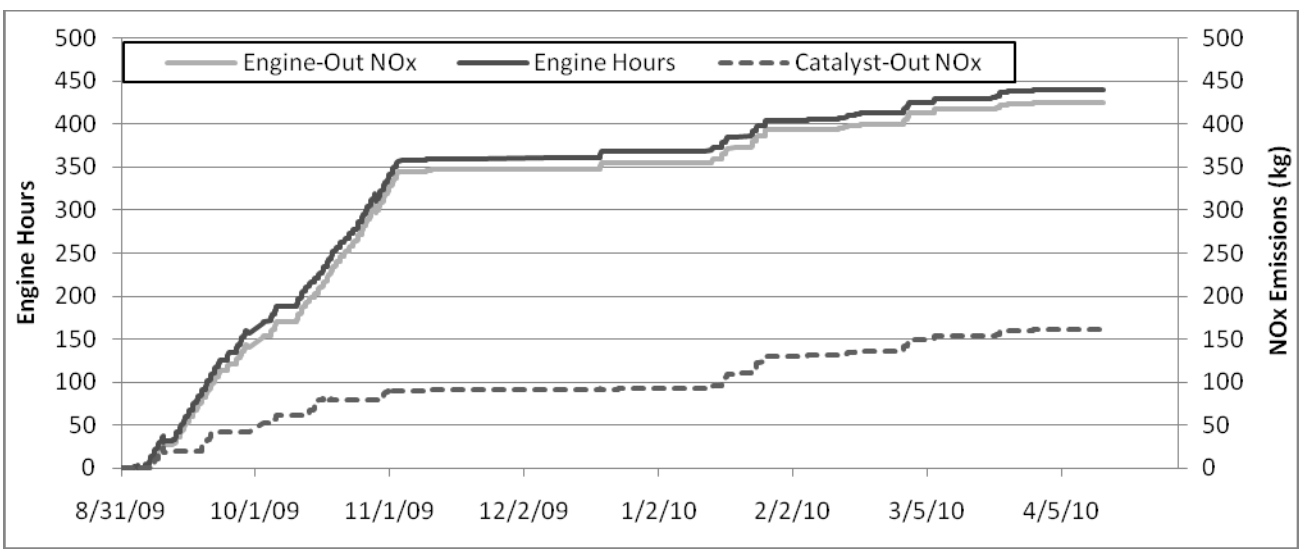


Figure 14: Cumulative operating hours and NOx emissions for the Starboard main engine

Due to software and wiring issues, the controls for the electric heaters used for DPF regeneration have not yet been activated, so that the main engine DPFs were subject only to passive regeneration from the end of September through the present. Given the high load experienced by the main engines under cruise conditions, it was anticipated that the DPFs would undergo passive regeneration frequently. Analysis of the exhaust pressure and temperature data logs, however, show no evidence of passive regeneration in the Starboard DPF assembly, and only a single identifiable regeneration event in the Port DPF assembly. Instead, it appears that the DPFs 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 appears to have reached and maintained a steady state; but one that allowed a significant amount of particulate matter to bypass the DPFs under cruise conditions.

Preliminary emission testing was conducted on the Starboard main engine on September 9, 2009. Test results are summarized in Figure 15 and in Table 2. The table 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. An estimate of the EPA weighted emissions pre-and post-control is also given in the table.

Table 2: Starboard main engine emissions vs load, pre and post emission control system

	Emissions (grams per kWh)					
	PM		NOx		CO	
Load	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	0.117
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 2 shows, 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 the 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.

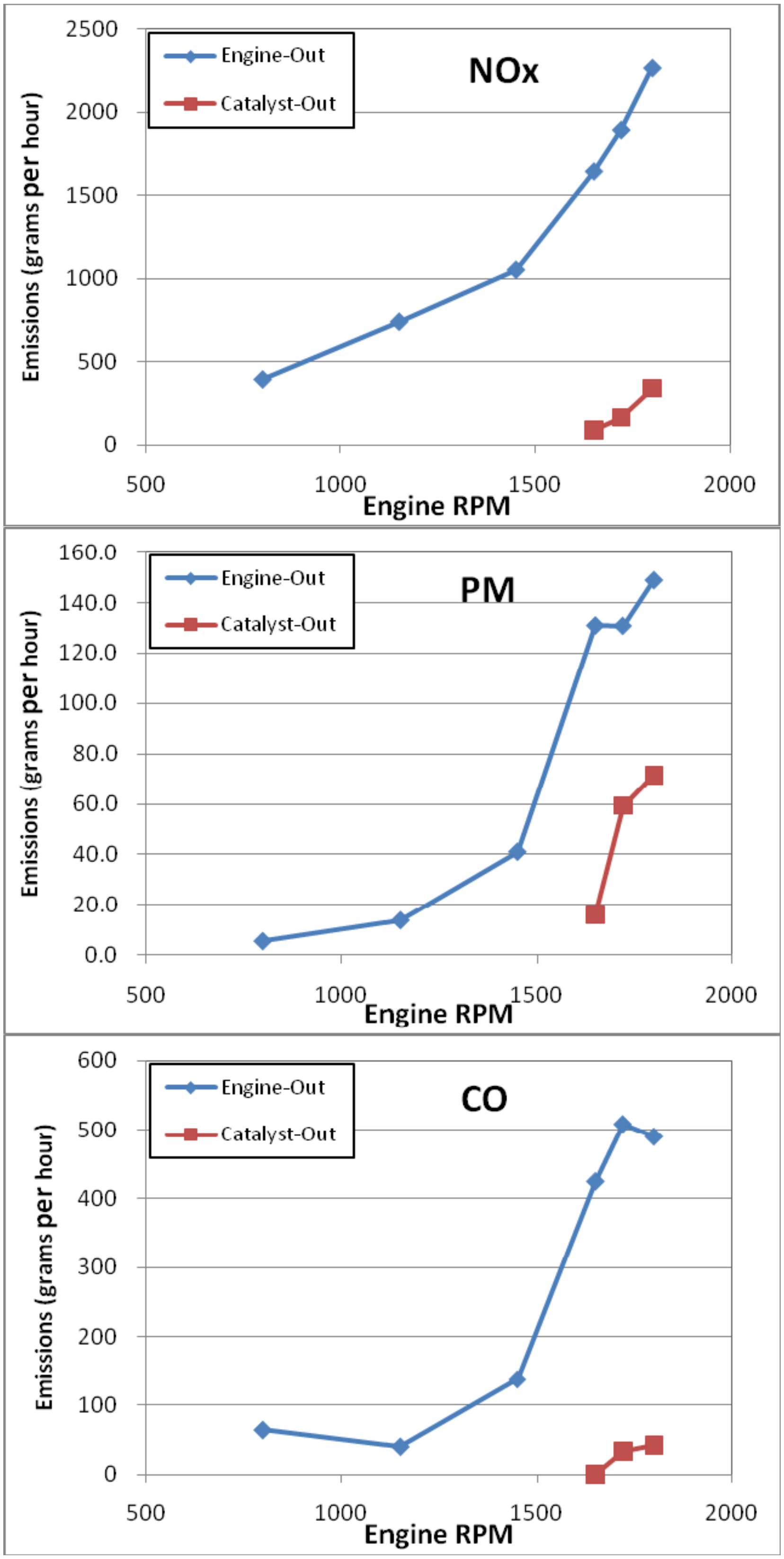


Figure 15: Preliminary emission results for the Starboard main engine

6. COMMERCIALIZATION PLAN

EF&EE's competitive analysis shows that we now dominate the small but rapidly-growing market for SCR systems in commercial boats. Our Compact SCR™ technology has set new standards for effectiveness, small size, and light weight in emission controls for commercial boats, giving us a 90% share of installed systems in North America. The public debut of this technology was in M/V *Gemini*, hailed as "the most environmentally friendly ferry in North America" in December 2008. Once the DPF regeneration issues are resolved, the SCR+PDF system on M/V *Royal Star* will demonstrate the achievement of similar emission levels starting with 20-year old Tier 0 engines.

6.1 Market Analysis

The original requirement for emission control on the WTA ferries was a mitigation measure stemming from the environmental impact analysis of the WTA's plan to double ferry service on San Francisco Bay. Now that the feasibility of SCR technology has been demonstrated, provisions of the National Environmental Policy Act (NEPA) and California Environmental Quality Act (CEQA) require that similar mitigation measures be specified for many major marine construction and dredging projects, as well as for any future expansions in ferry service. This will be true for federally-funded projects in Texas and much of the Northeast seaboard, as well as in California.

Replacing an old, high-emitting engine in a commercial boat with a new, lower-emitting one is among the most cost-effective diesel emission control options available (defined as dollars per ton of pollutants eliminated). For this reason, the Carl Moyer program has paid part, or all of the cost, of repowering many California vessels. All Moyer grants are required to meet a cost-effectiveness threshold, and some air districts award them competitively with cost-effectiveness as the main criterion. The new CARB harborcraft rule (17 CCR 93118.5) makes repowering and/or emission control retrofits mandatory for nearly all commercial boats operating in California. This requirement is to be phased in mostly between 2010 and 2016. To be eligible for grant funding, any repowering/retrofitting to comply with this mandate must be completed at least three years before the applicable compliance deadline, and only the "excess" emission reductions (earlier and/or lower than the CARB mandate) can be counted toward the cost-effectiveness threshold.

The combination of a Compact SCR™ system with a new, lower-emitting engine will typically double or triple the Moyer emission reduction achieved with the new engine alone. This can greatly improve the cost-effectiveness of a repower project, thus increasing the maximum amount of the grant and/or the chances of winning one. Where the existing engines are in good condition, a vessel owner can avoid the future costs of the mandatory retrofit by seeking grant funding now to install our Compact SCR™ or SCR+DPF systems. Especially for large, relatively modern engines, the Compact SCR™ system alone can allow a Tier 0 (uncontrolled) diesel engine to meet the CARB mandate, but smaller and older Tier 0 engines will require DPFs in addition to Compact SCR.

CARB has estimated that about 4200 vessels are subject to its harborcraft rule, of which 3300 are fishing vessels (commercial or charter), and 900 are in other categories (ferry, crew and supply, tug, tow, pilot, workboat). This latter group generally have larger engines, and are subject to more stringent emission requirements. We estimate that about half of these are potential customers for Compact SCR™ systems, along with a minority of the fishing fleet. Most vessels would need to retrofit at least four engines – both mains and both generators – at a total cost averaging about $250,000. Assuming that 400 of the 900 affected vessels retrofit rather than repowering, the California market alone would be $100 million.

EF&EE's sales to the commercial boat market are projected to increase from five vessels and $540,000 in 2008 to about 50 vessels and $11 million by 2012. We expect these to comprise a mix of Compact SCR™ retrofits (mostly to vessels equipped with Electromotive Diesel or other large engines), Compact SCR™ systems as original equipment on newly-built ferries, and Compact SCR™ plus DPF systems for vessels with smaller or older engines subject to the CARB retrofit rule.

6.2 Verification

The EPA and CARB have established procedures to *verify* that retrofit emission control devices are durable and effective when applied to a defined class of engines. In general, retrofit systems must be verified to qualify for grant funding or to be accepted as meeting CARB's mandatory retrofit rules. Both EPA and CARB require a durability demonstration and emission testing for verification, but the CARB procedure allows the retrofit device manufacturer to conduct these, while the EPA procedure requires that this be done by a third-party laboratory. Only one laboratory (the one that developed the EPA procedures) has been qualified to carry them out, and this laboratory is both very expensive and slow. Thus, nearly all emission control device manufacturers have chosen to verify under the CARB procedures.

EF&EE is pursuing CARB verification for its Compact SCR™ systems in marine propulsion engines, generating sets, and non-road construction and mining equipment. For marine engines and generating sets, we have agreed with CARB that the existing ferryboat installations will satisfy the durability requirement, so that we only need to carry out emission testing. We expect to obtain CARB approval for the test programs and to carry out that emission testing by the end of May, 2010. For the Compact SCR+DPF systems, we expect to submit an application for conditional verification as soon as the complete system reaches the minimum of 500 service hours, which should be about August, 2010. Final verification testing will undertaken when the system exceeds 1000 operating hours, probably late in 2010.

6.3 Value Proposition

EF&EE <u>sells</u> emission control systems, but what our customers <u>buy</u> is compliance with a regulatory requirement, contractual provision, or political mandate. Our customers are generally businesses or public agencies that are not experts on pollution control technology or regulations, but which must satisfy environmental agencies that do have such expertise. Lacking in-house expertise, the customer is necessarily dependent on the equipment vendor to ensure that the emission control system will bring the customer's engines into compliance. To the customer, then, *value* is the assurance that the customer's engines will meet all regulatory requirements–and will be accepted as doing so by the regulatory authorities–with minimal impact on the customer's operation. The customer's biggest fear in selecting emission control equipment is that the results won't satisfy the regulatory authorities, and that the customer will then be stuck with an expensive system while suffering regulatory sanctions such as fines and limits on operation.

EF&EE's value proposition to its customers is to relieve them of compliance risk by (1) engineering our emission control systems to the specific application, rather than force-fitting the application to one of a limited number of mass-produced products; and (2) assuming the regulatory risk – in effect, guaranteeing that the systems we sell will be accepted by the appropriate authorities as meeting applicable regulatory requirements. As experts in emission control system design and emission regulations, EF&EE is in a better position to control and mitigate regulatory risks than are our customers. Thus, EF&EE can add substantial customer value by taking on this risk, and then eliminating it through superior engineering and close coordination with air quality regulators.

EF&EE can also offer significant value to diesel engine and equipment dealers. These dealers generally have close relationships supplying parts and service to the major customers using their equipment, and are likely to be consulted by those customers for help in meeting emission regulations. The major engine manufacturers generally don't supply or support emission control retrofits, which leaves a hole in the dealer's product line that EF&EE will fill.

Another area in which EF&EE's expertise will add customer value is in applying for grant funding such as the Carl Moyer program. The rules governing these programs are complex and highly technical, making it difficult for most customers to apply on their own behalf. EF&EE is thoroughly familiar with these rules, having secured more than $25 million in similar funding for our consulting clients. EF&EE will advise customers and their engine dealers on the most effective strategies for obtaining emission control funds, and can prepare and submit the applications on their behalf – thus improving their odds of success.

6.4 STRATEGY

EF&EE has defined a 5 year strategy based upon a careful analysis of our target markets, competition, and the current economic climate:

- Obtain CARB verification for Compact SCR™ retrofit systems, with and without DPFs, by the end of 2010.
- Obtain EPA certification for Compact SCR™ installations on specific locomotive engine models, beginning with the EMD 12-710 commonly used in passenger locomotives (late 2010).
- Publicize the availability and effectiveness of Compact SCR™ systems and the availability of grant funding through articles and advertising in trade journals, and through presentations and displays at trade shows and conferences. Work closely with interested equipment owners and engine vendors to submit applications for funding.
- Work directly with major public-agency equipment owners such as Metrolink, Caltrans, Amtrak, WETA, and Washington State Ferries to conduct pilot programs, prepare emission control plans, and apply for state and federal funding.
- Maintain liaison with state and local air pollution control agencies responsible for permitting stationary sources, and for approving environmental impact mitigation plans

on major construction projects. This will include both direct contact with individual agencies and involvement with agency associations such as CAPCOA and STAPPA/ALAPCO.

- Work to establish a network of diesel engine and equipment dealers who will sell Compact SCR™ products as a complementary product line. Dealerships will generally be non-exclusive, so that the local Caterpillar, Cummins, and Detroit Diesel dealers could each offer our products to their customers. This network will be supported by regional service and training centers. It will initially focus on California, and then expand to Texas and the Northeast. Dealers will be offered discounts of about 20-30% from list price, as well as technical and marketing support.
- Establish a national sales staff to (a) support the dealers and (b) sell directly to major accounts, and to customers where no engine dealer is involved.
- Maintain customer relationships through after-sales service (coordinated through the dealer, where applicable). This will include offering maintenance contracts and "turnkey" contracts in which EF&EE would take on all responsibility for maintaining the SCR system, keeping the system supplied with urea, remote monitoring of system performance, and the preparation of periodic reports to regulators where these are required. EF&EE will also offer free assistance in planning to meet upcoming regulations.