Performance and Durability Assessment of Two Emission Control Technologies Installed on a Legacy High-Speed Marine Diesel Engine

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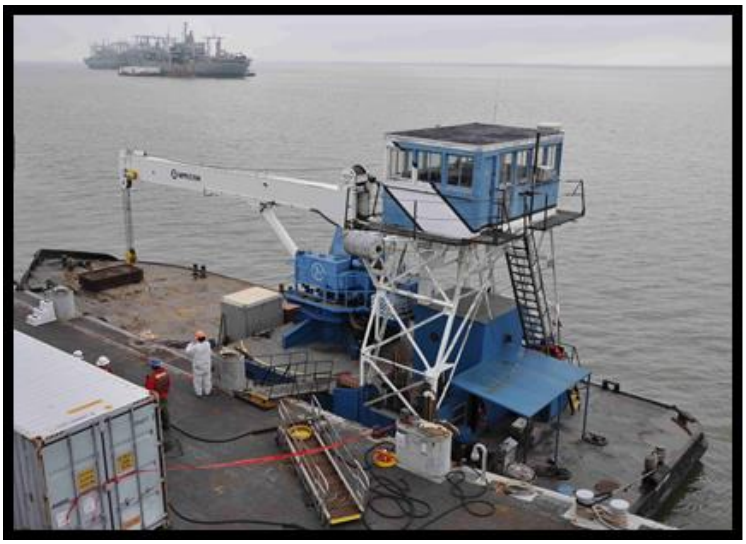


The Navy pilot program investigated cost-effective technologies to reduce emissions from legacy marine engines. High-speed, high-population engine models in both commercial and Navy fleets were targeted. Emission reductions were sought that would minimize fuel penalty as well as installation and operating costs. Navy operating conditions and fuels limited options. Five highly rated technologies were laboratory tested on a Detroit Diesel Corporation 12V-71N engine using two military and three alternative fuels. Two control technologies were then shipboard tested (baseline, 1-year early degradation, and 9-year late-life). Conclusions and recommendations are provided to inform application of these and similar emission control technologies within both commercial and Navy fleets.

INTRODUCTION

The Navy Pilot Emission Control Program (NPECP) was initiated in 2001, after both the Environmental Protection Agency (EPA) and the International Maritime Organization (IMO) established marine engine emission regulations. Marine vessels constituted the last transportation sector for regulation. Therefore marine vessel criteria pollutants, particularly nitrogen oxides (NO_x) and particulate matter (PM), received increased scrutiny. International and domestic marine engine regulations (phase-in start dates of 2000 and 2004, respectively) were driven by health effects and environmental impacts.

The U.S. Navy assessed its contribution to the domestic marine emission inventory, the operational impacts of expected new engine controls, and the feasibility of selective application of control concepts on existing engines. Unique Navy operational requirements, challenges posed by the marine environment, and distinct marine engine models render the operating mechanisms of some on-land application technology concepts ineffective and enhance the viability of other concepts.

The objective of the sponsorship-leveraged NPECP is to explore the feasibility of carefully selected emission controls, entailing varied technological approaches, and to evaluate those with greatest potential. A laboratory developmental assessment was followed by a shipboard evaluation. Effective technology concepts applied to high-speed, heavy-duty diesel (HDD) engine models, prolific on both land and sea, could be subsequently scaled to medium-speed marine engines used for some Navy ships and most Military Sealift Command (MSC) cargo vessels.

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MARINE ENGINE EMISSION CONTROL NEED

When regulations were first legislated, marine engine emissions were a significant contributor to the national inventory (EPA 2008). Without regulation, these emissions were projected to grow substantially by 2030. As a proportion of domestic mobile sources, EPA data indicate that 2001/2002 emissions from baseline compression ignition (CI) marine engines (commercial [coml.] and recreational) account for 8.8 percent (%) of NO_x and 8.9% of $PM_{2.5}$. Projected 2030 CI marine engines emissions (Tier 1 and 2 regulations in effect, but no Tier 3 and 4 regulations) would account for 28.0% of NO_x and 33.5% of $PM_{2.5}$ from domestic mobile sources.

Similarly, as a proportion of all domestic sources, 2001/2002 emissions from baseline CI marine engines account for 5.0% of NO_x and 2.0% of $PM_{2.5}$. Projected 2030 emissions (Tier 1 and 2 regulations in effect, but no Tier 3 and 4 regulations) from baseline CI marine engines account for 11.9% of NO_x and 3.9% of $PM_{2.5}$ from domestic sources.

However, the proportion of marine engine emissions in "nonattainment" area counties with active ports is much higher. Concentrations of marine engine emissions in 2001/2002 can range to greater than 42% of NO_x and 53% of $PM_{2.5}$ from domestic mobile sources. Projected 2030 concentrations of Houston counties' marine engine emissions (Tier 1 and 2 regulations in effect, but no Tier 3 and 4 regulations) increase to 46% of NO_x and 85% of $PM_{2.5}$ from domestic mobile sources.

Regulation

Marine engines in U.S.-owned vessels have been regulated on a dual track (EPA 1999):

1. EPA regulations target Category 1 (Cat 1) (>37 kW and displacement/cylinder [disp] <5 L) and Cat 2 (5≤ disp < 30 L) new engines and marine distillate fuel for vessels in domestic operation – Tier 0 and 1 remanufactured engines are also now regulated;
2. IMO regulations (for engines rated >130 kW and both marine bunker and distillate fuels) were applied by EPA to Cat 1 and 2 engines on ships operating internationally and all Cat 3 (disp ≥5 L) engines.

EPA sought and facilitated greater harmonization of emission standards between the two organizations.

Services' Responsibility

The Navy is required to comply with the Clean Air Act (CAA) requirements and related federal, state, and local regulations "in the same manner and to the same extent as any nongovernmental entity" (OPNAVINST 2014). Navy acquisition policy dictates equipment procured "performs the missions and functions for which it is organized or designed, in full compliance with all applicable environmental laws and regulations," while "investing in future compliance to the extent that is affordable." When deemed impractical or unaffordable, the Navy and other Services procure engines not in commercial compliance according to EPA's provision for automatic or requested national security exemptions (NSEs) (EPA 1999, Schihl 2009). Because of global operations and the primary use of military fuels, EPA has also provided a fuel NSE for deployable vessels (EPA 2004). The Services must maintain inventories of engine NSE and fuel NSE equipment.

Land installations and vessels dedicated to or home ported to those activities must meet conformity requirements in nonattainment areas. Inventories of emissions generated by that equipment must also be maintained. For emission reductions not required by CAA or state implementation plans (SIPs), emission reduction credits may be earned and used as offsets or traded to other Service installations or federal agencies within the same air quality district (AQD) (OPNAVINST 2014).

The Navy must both anticipate the impacts of complying with new and existing engine emission regulations and ensure that control options are available to achieve conformity standards in geographical areas designated as "nonattainment" for one or more pollutants. Simply applying automatic or requested engine NSEs, and similar fuel NSEs do not advance the Navy Fleet toward engines and fuels that are in commercial compliance.

Technology Availability

Since highway, nonroad, and rail transportation sectors were regulated prior to that of marine, emission controls have typically been developed for engines employed in those sectors and later adapted to marine engines. However diesel engines, operated in the marine environment and required to fulfill a variety of Navy missions, possess unique design constraints and advantages. Constraints include requirements for a high power-to-weight ratio; high reliability, availability, maintainability, and durability (RAMD); tolerance to standard military-specification highly stable fuel and lubricating oil; conservative maximum power rating; and low load factor (Corbett 1997, Hughes 2000, Stapersma 1998). The operational constraints result in a higher proportion of partial load operation and subsequent effects of less complete combustion and lower exhaust temperatures. An advantage to marine engine installations is the plentiful raw water cooling supply, however exploiting this cooling source is typically more difficult than that of ram air on land vehicles.

EPA provides certification to original equipment manufacturer (OEM) control technologies integrated on production engines and aftermarket control technologies that can be applied to existing engines. The smaller population and greater longevity of marine engines are a disincentive for OEMs and aftermarket equipment manufacturers adapting and commercializing applicable emission controls. Available emission controls are also not necessarily viable in Navy or general military service.

CONTROL OPTIONS

The NPECP sought to identify or develop NO_x and PM emission control technologies that are effective, reliable, and durable in the Navy marine environment (operation, fuels, installation limitations, and environmental factors) and do not compromise mission-based operating capabilities (engine power density, fuel consumption, and performance). The controls may be applied to either new or existing vessels in which new engines are to be installed. They may also be applied to existing vessel engines to which the technologies are approved for application.

In the development process of such technologies, the intention is to ensure that ship design offices, shore activities, and Type

Commanders have access to effective and tested NO_x and PM reduction techniques and hardware. The acceptance and insertion of control technology can be an element of a criteria pollutant inventory reduction strategy in nonattainment or maintenance (threshold of nonattainment) areas necessitated by weapons-basing decisions, operational tempo, military growth, earning and trading emissions credits, and/or public relations. Initial steps toward appropriate technology identification and development include conducting concept feasibility analyses and demonstrating satisfactory performance over time.

Requirements for either new or existing marine engine emission controls that would be viable in Navy service include: operator invisibility, operating condition insensitivity, fuel type flexibility, wide-ranging fuel sulfur and lubricity compatibility, high reliability and durability, compactness, and simplicity.

New Marine Engines

Shipboard engines have been regulated for only 11-16 years (from the most recent [37-130 kW] to the first regulated engines [<37 kW installed shipboard]). The Navy procures both NSE engines and engines in commercial compliance.

Constraints to Navy procurement of new engines in commercial compliance follow: incompatible physical size and weight, intolerant to Navy fuels, requirement for fluids not supplied, nonviable for operating conditions and mission requirements, and complication to configuration control for a vessel class.

Opportunities to progress toward commercial compliance and achieve emission reduction exist within these new engine procurement constraints. Compliant engines with in-cylinder controls are most compatible with physical space and weight constraints. However, other controls may also be compatible and sufficiently tolerant to military fuels and ship systems.

Granted, engines in commercial compliance are typically not the lowest-priced candidates for a newbuild or vessel undergoing reengining. New engine emission reduction development and hardware impact engine cost. Within the Navy, there is currently no broadly accepted procedure for estimating the value of the higher cost and comparing that to the emission-reduction benefit. Therefore, it is more difficult to justify the cost increase for engines in commercial compliance when compared to those in commercial noncompliance.

Were such a tool available, the affordability component of a newbuild engine selection decision could be quantified and, where favorable, justified. Presumably, more engines in commercial compliance could then be objectively considered and introduced to the Fleet, with the higher cost justified.

Existing Marine Engines

EPA regulated existing engines after new engines (EPA 2008).

Constraints to Navy emission reduction on existing engines are similar to those for accepting new compliant engines. However, configuration control challenges would begin with the first existing engine modified.

Opportunities for emission reduction through existing engine commercial compliance are also similar to those for new engines. EPA addresses several categories of modification as follows, with each yielding opportunities for emission-reduction technology insertion via engine replacement or retrofit:

<u>Engine rebuild</u> requirements apply to measures that significantly increase service life. A rebuild must conform to the model year original configuration, all emission-impacting components and parameters must meet OEM requirements, and records (detailing hours of operation and work on emission-impacting components) must be kept for two years or more.

<u>Engine remanufacture</u> (all liners inspected or replaced in <5-yr period) requirements encompass Tier 0-2, Category (Cat) 1 and 2, model year 1973 or later, and rating ≥600 kW. Retrofit installation of EPA-certified OEM kits (if available) is required, yielding ≥25% PM reduction with no NO_x increase, complying with record-keeping, and labeling the engine as remanufactured.

<u>Engine replacement</u> requirements dictate that the replacement be certified to the current tier standards. If in so doing the replacement cannot meet physical or performance requirements, EPA requires the installation of the highest tier engine that meets those requirements. A used replacement engine must have at least the same model year as the engine it is replacing.

Fuels

Although there are limited military and substitute fuels required for global operation, within current policy and practice there are fuel-based avenues for reducing Navy cumulative emissions.

Constraints

Shipboard fuel preference requirements, in descending order, for all shipboard power plants (diesel engines, gas turbines, and steam boilers) are as follows:

- <u>Primary</u> (continuous use) – NATO F-76 distillate;
- <u>Substitute</u> (extended use) – JP-5 (NATO F-44) and coml. marine gas oil (MGO) according to Naval Sea Systems Command (NAVSEA) purchase description (PD); and
- <u>Emergency</u> – MGO conforming to ISO 8217 Grade DMA.

Although fuel sulfur averages are of interest, it is the maximum sulfur limits that indicate the levels that could be encountered in extended operation. These limits are as follows (at time of program start / currently): F-76 (10,000 ppm / 15 ppm); JP-5 (5,000 ppm / 2,000 ppm); MGO (NAVSEA PD) (10,000 ppm / same); and MGO (DMA) (15,000 ppm / same).

Opportunities to progress toward commercial compliance and achieve emission reduction exist within the constraints of military fuels: selecting cleaner-burning military fuels, tailoring properties of the existing in-use military fuels, and expanding the selective use of alternative fuels and fuel additives.

RETROFIT PATH

Identifying the most cost effective route for emission control retrofits in the Navy will yield the highest likelihood of favorable consideration and success.

Investigation Subset

Pursuit of a strategic NPECP target subset led to a focus on high-speed engines for which there was substantial history of emission control in highway and nonroad transportation sectors. That history could include the application of emission controls on the same base engines within the Services. Though the highway and nonroad versions of the base engines are not marinized, the accumulated experience is significant and relevant for the Navy's marine versions of the same engines.

Service Craft and Small Boats that are active in the Navy Fleet number 2,100 small boats, 500 service craft, and 400 ship's boats. These vessels include approximately 50 types of small boats and craft, with hundreds of length overall (L_{OA}) variations.

High-Speed Two-Stroke (2S) Engines (marine high-speed diesel) powering these vessels number approximately 4,200. Within this category of relatively small (predominantly HDD sized) engines there is a significant subset of high fuel-consuming and fuel-polluting 2S engines; about half of these engines are naturally aspirated (NA). A portion (~1,040) of this subset was selected for the NPECP as a target engine group for the feasibility demonstration of emission control and fuel efficiency enhancing technology concepts. This engine group includes the largest of the Navy's high-speed 2S engines; with each possessing 12 or 16 cylinders, they represent relatively low-hanging fruit for the application of cost-effective emission control technologies. An average 496,000 barrels of diesel fuel are consumed annually by this target engine category. OEM factory emission rates for these engines indicate that, on an annual basis, 9,672, 138, and 412 metric tons (MT) of NO_x, HC, and PM are produced, respectively. With expected lifetimes of 30 or more years, repowering these vessels at ~$150,000-300,000 with compliant engines would be more difficult to justify than lower-costing hardware and installation retrofits. Depending on emission control technologies selected, the cost of retrofiting could be a fraction of that of a repower (replacing an existing legacy engine with a newer technology engine).

Target Engine Group Vessels include the 41-m Landing Craft Utility (LCU) and 17-m and 23-m Landing Craft Mechanized (LCM). These service craft are prime examples of the need for emission controls and a thorough assessment of the benefits and liabilities of applying controls. The 174 LCUs and LCMs in Navy and Army service in 2002 are equipped with four Detroit Diesel Corporation (DDC) 71-series 12-cylinder engines – two for propulsion and two for power generation (Jane's 2001).
Investigating emission control concepts for these vessels provides options for responding to conformity-induced limitations, but also addresses an immediate hazardous environment for operators. Complaints from those working with these vessels in the well deck of each mother ship (whether Landing Platform Dock [LPD], Landing Helicopter Deck [LHD], Landing Helicopter Assault [LHA], Landing Ship, Docks [LSD], and Landing Ship Tank [LST]) include eye and throat irritation from the exhaust. Sailors working in the well decks can log up to 18 hours at a stretch, lighting off and warming up the engines and lashing down the vessels. The engines are frequently gunned as each LCU or LCM vessel is maneuvered into position to embark or disembark to or from the mother ship. The well decks are equipped with vintage 1950s ventilation systems that are grossly inadequate. Some sailors have elected to wear goggles, but the expressed crew preference is for gas masks. Therefore, although the need for conformity options was a primary NPECP objective, health and safety in similar applications provides a further distinct objective and offers the possibility of directly improving sailor quality of life.

Cost

Emission control technology insertion must be cost effective for favorable consideration. For exploratory projects to materialize to actual technology insertion there must be objective assessments of substantial positive return on investment (ROI).

Scheduled Overhaul Preference over Special Install is one means of reducing the cost for retrofitting emission controls. During overhaul, emission-reducing power assembly, injection system, and turbocharging components can be interchanged with stock components. Cost avoidance includes that of downtime and the extra effort associated with a special installation.

Fuel Penalty, along with associated trade-off increases in HC, PM, and CO emissions, is a challenge to minimize as combustion parameters are tailored to reduce NO_x.

Reliability must be maintained in order to achieve a positive ROI. In-cylinder measures often yield a higher potential for maintaining reliability than do aftertreatment (AT) controls. However, many AT technologies have accumulated substantial service history, indicating that AT is not necessarily less reliable than in-cylinder technologies. In addition, controls that are certified by EPA or California Air Resource Board (CARB) also possess a higher level of reliability potential.

Benefit

Factoring into a positive ROI assessment are overall Fleet inventory reductions, specific local (vessel crew or port facility) and regional reductions, and showcase-project public relations.

Emission Reduction value quantification (reference previous New Marine Engine section) provides the most effective means for comparing benefit to cost.

DOWNSELECT

Emission control objectives may be achieved by new engine installation in vessel newbuilds and attrition-based engine replacement or technology retrofit. The NPECP retrofit consideration corresponded with an early EPA goal to reduce emissions from at least 10,000 existing diesel engines (EPA 2000). Upon selection and evaluation of retrofitable controls, the NPECP's intent is to disseminate the results among Navy field activities to inform selective retrofits.

Process

To narrow the field of technology options, control concepts solicited from the emission control industry were targeted to a well-defined target engine group (NAVSSES/CBD 2000).

Concepts accepted for further investigation were rated and those selected for lab testing were determined to have high potential for effective emission control.

Commerce Business Daily (CBD) Solicitation sought commercial off the shelf (COTS) or edge of the shelf (EOTS) emission control technologies that are tolerant of marine-specific constraints: high sulfur tolerance (F-76 and MGO 10,000 ppm sulfur limit), low load factor operating profiles (10-60%) with 90% of operation at 50% load the norm for large Navy ships (Corbett 2003, Khair 1999, Stapersma 1998), high proportion of wet exhaust installations (raw water is sprayed into the exhaust stream to cool the gases and the mixed gas and water is discharged close to water level through the transom or side of the hull), low exhaust gas temperatures (232 – 427 ºC) by virtue of the 2S engine design, low back pressure tolerance (76 – 127 mm Hg) resulting from the naturally aspirated (NA) design, and high emissions (12 – 31 NO_x, 0.3 – 2.1 PM, 2.7 – 5.4 SO_2, 0.2 – 0.7 HC, and 8.0 – 66 CO [g/bkW-hr]) (NAVSSES/CBD 2000).

Proposal Rating was completed using a qualitative assessment of U.S. Navy operation and marine environment applicability; technology success potential, cost, marine application, field use, industry acceptance – as indicated by published and peer-reviewed data, and commercialization; and a quantitative cost-benefit evaluation to rate the proposed technology submittals.
Acceptable emission controls are compatible with the specified environment, operation, and engine design vintage. Disqualifying factors include the following: catalyst sulfur poisoning, water intrusion from the exhaust exit port, imposed exhaust restriction, high proportion of low load operation and insufficient exhaust temperature to activate catalysts or passively regenerate filters, excessively high emission rates to be accommodated by a reasonably sized control unit, concerns with system hardware size and weight, imposed fuel penalty, RAMD reduction, and cost-effectiveness. In addition, acceptable control concepts can be fielded and commercialized for existing engine applications. This can be conducted more cost effectively than an engine repower.

Lab Test Selection was made based on the proposal rating that included estimated emission reductions and installation and operating cost. Of the thirteen submittals received, NAVSSES selected the following five highest rated NO_x and PM reduction technology concepts – (EOTS [item 1] and COTS [items 2-5]):

1. Air humidification via post-compressor service water injection into intake air;
2. Electrically regenerated active diesel particulate filter (ERADPF);
3. In-cylinder-effected exhaust gas recirculation (EGR);
4. In-cylinder catalytic coating developed from ferrocene fuel-borne additive; and
5. Sac-volume reduction of injection nozzles.

These were later reviewed and endorsed by a team of emission control experts from Southwest Research Institute's (SwRI's) Dept. of Emissions Research (Khair et al, personal communication). Based on recommendations from program sponsors (Navy/USMC Fuels/Lube Oil [F/L] Integrated Product Team [IPT], CARB, and Department of Energy [DOE]) and Navy needs, four alternative fuels to the primary Navy F-76 fuel were selected to assess each technology: JP-5, ultra-low sulfur diesel fuel (ULSD), Fischer-Tropsch, and a B20 vegetable methyl ester biodiesel fuel (fuel analysis results in Appendix A) (Hughes 2001). The ULSD had been formulated in 2000 by the Dept. of Energy (DOE) to represent a future market ultralow sulfur diesel fuel for on-road vehicles. The fuel was used in the Diesel Emission Control Sulfur Effects (DECSE) program. Data from that work provided the basis for the legislation of diesel fuel at or below 15 ppm sulfur.

LAB TEST PHASE

By attaining steady-state operating conditions that are representative of actual operation and doing so in a controlled environment, the laboratory testing was designed to provide a basis for valid comparison of technology and fuel combinations.

Procedure

Prior to test data collection, the DDC 12V-71N test engine (Shore Intermediate Maintenance Facility [SIMA] overhaul unit: model no. 7122-7000; serial no. 2VA039449; 1974 model [shipped 27 August 1974] and rated 317 bkW [425 bhp] at 2300 rpm [N70 injectors]), in baseline configuration, underwent 125 hours of cycled operation for break-in and emissions stabilization. F-76 naval distillate containing 5,900 ppm sulfur (worldwide average for F-76) was utilized for baseline fueling.

ISO 8178 cycles D2 (1800 rpm) and E5 (2300 rated rpm) modes were utilized. Cycle D2 is for "Constant speed generating sets with intermittent load," and cycle E5 is for "Marine Diesel engines for craft less than 24 m in length (propeller law)" (ISO 1998). The baseline engine was operated at D2, E5, and rated torque combined cycle steady-state conditions, then with each technology control applied (following adjustments to optimize experimental hardware), and finally with several combinations of the most effective and complementary concepts (Table 1).

Table 1. Lab test matrix

Cycle / Condition	Mode	Test Point	Rpm (%RS*)	Load (%FL**)	Rpm (actual)	BkW (actual)
E5	1	1	100	100	2300	324
	2	2	91	75	2093	243
	3	3	80	50	1840	163
	4	4	63	25	1449	81
	5	5	idle	0	1200	0
Rated Torque		6	91	75	1600	290
D2	1	7	100	100	1800	257
	2	8	100	75	1800	193
	3	9	100	50	1800	129
	4	10	100	25	1800	66
	5	11	100	10	1800	26

*NOTE: Rated speed
**NOTE: Full load

Measurements included the following:

1. Basic performance parameters (speed, torque, temperatures and pressures, fuel consumption, lube oil consumption, intake air flow, and ambient conditions);

2. Criteria gaseous and PM emissions on a gravimetric basis in accordance with ISO 8178, Part 2 and 3 (ISO 1996); and
3. PM physical characterization and chemical analysis (Table 1 test points [TPs] 1, 5, 6, and 9).

Criteria Pollutants were measured by NAVSSES.

PM Characterization was conducted by NAVSSES downstream from the secondary dilution tunnel.

Exhaust Speciation was conducted at the NAVSSES laboratory by Oak Ridge National Laboratory (ORNL). Exhaust chemistry speciation and PM analysis were conducted on each of the five fuel types and several combinations of emission controls.

Instrumentation

Laboratory testing was conducted in the NAVSSES marine Diesel Engine Test Facility (DETF) that includes two sound-isolated 6 x 12 m test cells (accommodating a conventional 3,000 bkW marine diesel engine or combinations of smaller engines) and an adjacent 12 x 18 m teardown area. Emissions analysis instruments, were located within and adjacent to the test cell. PM filters were conditioned and weighed in laboratory isolated clean rooms. Fuel was piped to the test cells from twin 662,000 L storage tanks, an alternate fuels tank (19,000 L), twin 1,900 L day tanks, or portable in-cell tanks.
Gaseous constituent emissions were measured using Rosemount analyzers and CAI HFID. PM was measured by partial flow sampling system (PFSS), micro-dilution tunnel with twin parallel filters in a Sierra BG-2 bench and physically characterized by Scanning Mobility Particle Sizer (SMPS) (3936 [3085 for nano {3-150 nm} and 3081 for long {10-1000 nm} particles measured by Differential Mobility Analyzers {DMAs}]), and Condensation Particle Counter (CPC) (3025) with a 20-10^7 particles/cm^3 concentration range (Fig. 1).

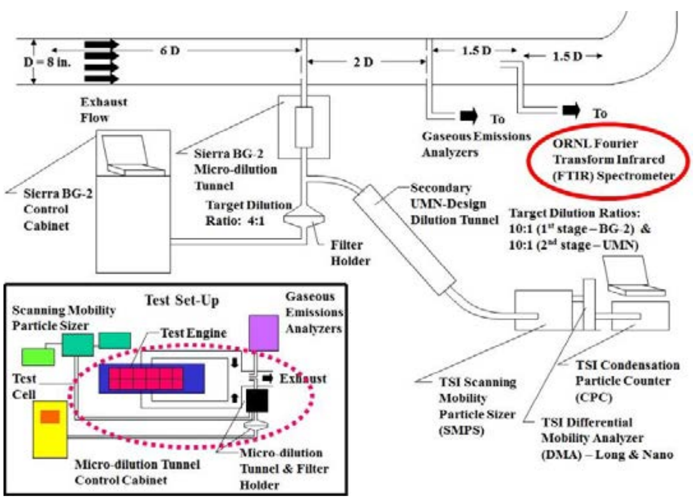

Fig. 1 NAVSSES lab test set-up and sampling train

Sampled exhaust was also drawn through a second micro-dilution tunnel for measurements of PM on standard gravimetric filters for soluble organic fraction (SOF) extraction and determination of sulfates, volatiles, organic carbon (OC), elemental carbon (EC), and aldehydes with the di-nitro phenylhydrazine (DNPH) method. Undiluted exhaust was used to measure NO_x, CO, CO_2, HC, aldehydes, and SO_2 from a Fourier Transform Infrared (FTIR) Spectrometer (Nexus 870) with a heated multipath gas cell (Fig. 2).

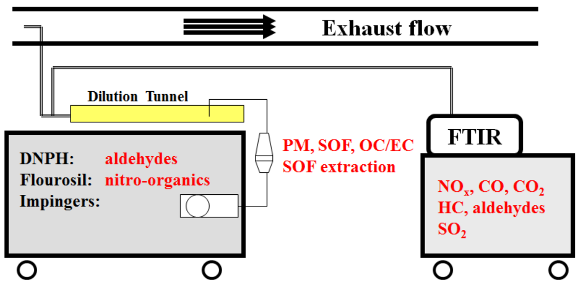

Fig. 2 ORNL lab sampling train and analytical tools

Results

Of the five emission control technologies selected, three proceeded through lab testing and two (water injection and reduced sac volume injectors) did not. For those two, sufficient development was not demonstrated by the technology providers to install, tune, and match the controls to the engine system in the memorandum of understanding agreed-upon set-up time. The supplied intake air humidification system required too much additional development to customize it to the test engine and acquire acceptable engine performance. Vendor supply and support for the reduced sac-volume injectors proved inadequate to achieve an operational modified engine configuration.
Testing proceeded with the following technologies: ERADPF from Rypos Inc., in-cylinder-effected EGR from Clean Cam Technology System (CCTS) Inc., and in-cylinder catalytic coating developed from Catane (Cat) Inc. (ferrocene fuel-borne additive). Both single fuels and controls were tested, as well as some fuel and control combinations. The ERADPF experienced a valve failure after successful operation for three tests. However, the failure analysis isolated the failure cause and the technology provider had already placed in production the upgraded components to correct the problem.
Engine performance for the five test fuels and three control technologies are provided for both the E5 and D2 cycles in Fig. 3. Sufficient engine run time for conditioning on Cat could not be achieved, however early indications of its benefit were explored nonetheless.
The comparison of fuels on the test engine indicate a pronounced brake specific fuel consumption (bsfc) reduction for the E5 cycle with both ULSD and F-T and for the D2 cycle with F-T. All fuels tested as alternatives to F-76 exhibit one or more beneficial NO_x, PM, or bsfc reductions relative to the F-76 baseline. Although each could pose logistical, stability, durability, and/or stability challenges for even selective introduction to Fleet vessels, specifications could likely be tailored to make those effects negligible. Each could be combined with acceptable emission controls to achieve significant emission reductions.
Limited emission control combinations were tested because of

technology installation and set-up problems. Those issues led to the removal of two of the five controls under test. The weighted cycle results indicate that each individual control and combination display a bsfc E5 improvement and a D2 penalty.

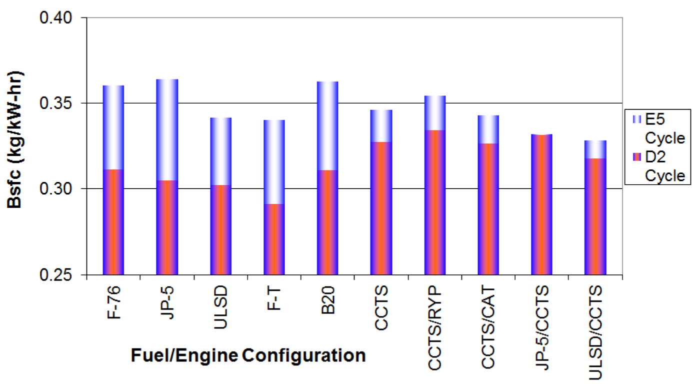

Fig. 3 Brake-specific fuel consumption

All emission control technology combinations significantly reduced NO_x (Fig. 4). CCTS increased PM substantially, but was effectively cleaned up when paired with the Rypos ERADPF (Fig. 5). Therefore, by combining the CCTS with Rypos ERADPF AT PM filtering, the CCTS NO_x benefit can be maintained without the aid of an alternative fuel and without a severe bsfc and PM penalty.

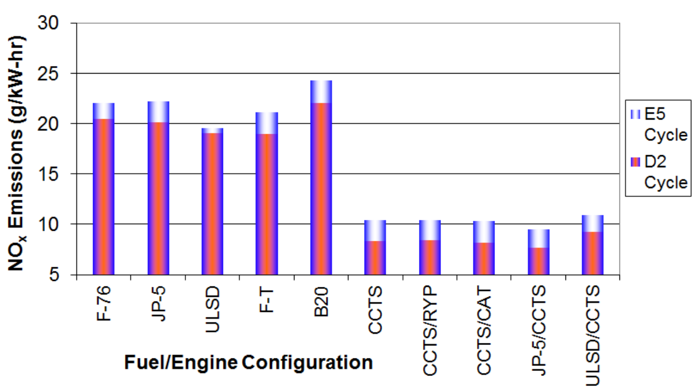

Fig. 4 Brake-specific NO_x emissions

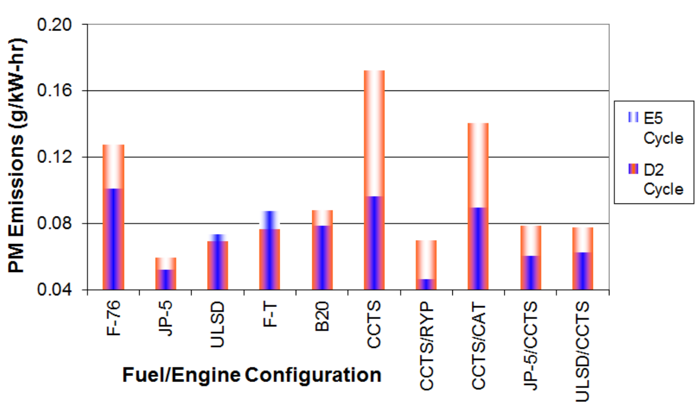

Fig. 5 Brake-specific PM emissions

Only ULSD and F-T produced significant E5 cycle NO_x reductions (11% and 4%, respectively), while JP-5, ULSD, F-T, and B20 all produced significant PM reductions (48%, 33%, 13%, and 22%, respectively) (Figs. 4 and 5). JP-5 and B20 each exhibited a small E5 cycle bsfc penalty (1%), while ULSD and F-T resulted in significant bsfc improvements (5% and 6%, respectively) (Fig. 3). In addition, the CCTS and Rypos controls coupled together produced 53%, 54%, and 2% E5 cycle reductions in baseline NO_x, PM, and bsfc, respectively.
A comparison of the three emission control technologies for each cycle indicate greater NO_x and PM reductions on the E5 cycle, along with a small bsfc reduction (Fig. 6). The D2 cycle produced PM increases for both CCTS and Cat, a lesser PM reduction for Rypos, and small bsfc increases (Fig. 7).

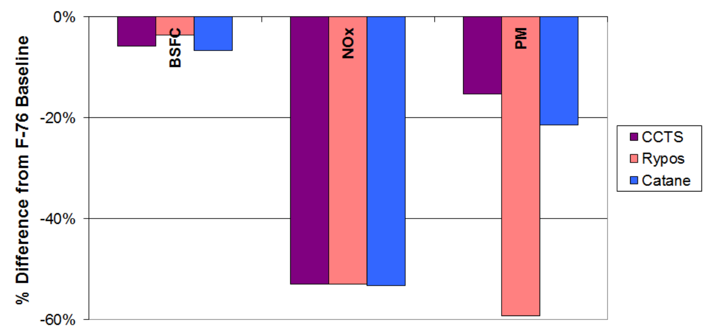

Fig. 6 Percentage difference from F-76 baseline – E5 cycle

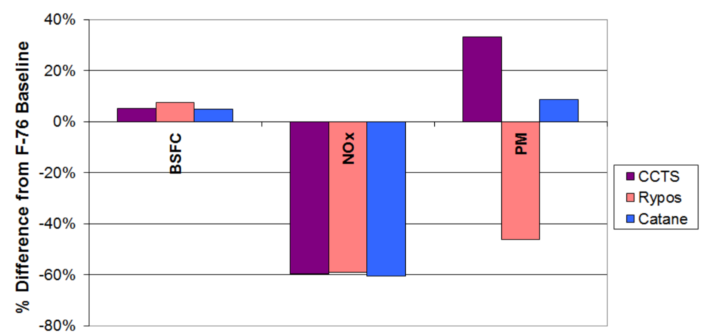

Fig. 7 Percentage difference from F-76 baseline – D2 cycle

PM physical characterization was conducted at the Table 1 conditions TP1 (E5 cycle rated speed and load) and TP9 (D2 cycle rated speed and 50% load). Geometric mean diameter and PM number concentration for the tested fuels and engine configurations are presented in Figs. 8 and 9. Although individual size and size-specific number distributions further distinguish the sampled PM, the TP1 and TP9 comparison charts indicate general changes relative to PM total mass flow rate. At each test cycle operating mode, the relative brake specific PM emission rates differ between fuels and engine configurations. These rates do not match that of the weighted cycle rates (Fig. 5). Although the NO_x-optimized CCTS substantially increases PM at TP1, the Rypos ERADPF exhibits effective AT filtering, decreasing PM number concentration and mass by 90% and 64% (TP1) respectively. For TP9, the ERADPF decreases PM number concentration and mass by 70% and 45%, respectively.

From the F-76 baseline, the Rypos ERADPF reduces TP1 PM number concentration and mass by 90% and 32%, and TP9 by 78% and 57%, respectively. ERADPF PM removal efficiencies for TP1 and TP9 are consistent with that reported (Yelverton 2015) when using Tier 2 and 3 ULSD-fueled four-stroke (4S) diesel generating sets of similar engine displacements.

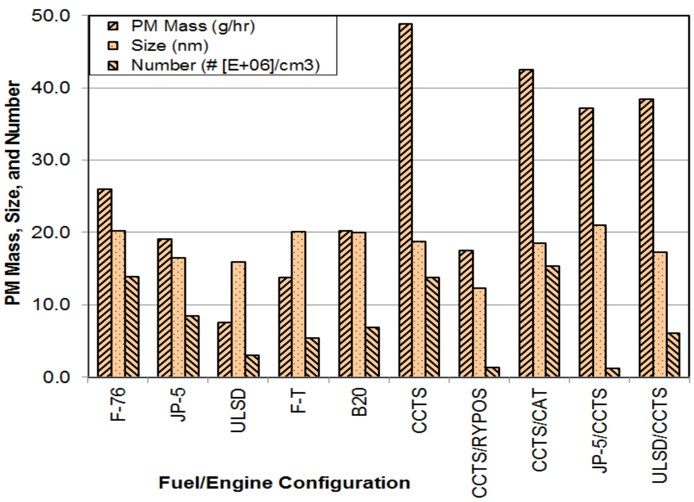

Fig. 8 Total PM mass flow rate, mean size, and volumetric concentration for TP1

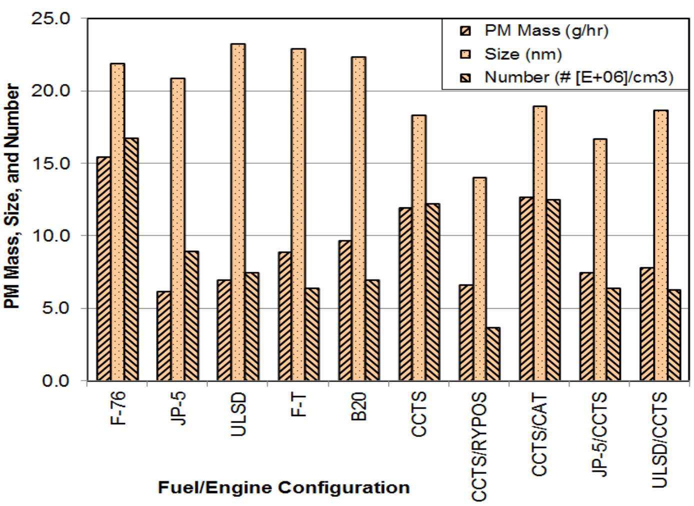

Fig. 9 Total PM mass flow rate, mean size, and volumetric concentration for TP9

Both the CCTS internal EGR and the Rypos ERADPF reduced PM across the size spectrum (Table 2). Reductions in total PM are also reflected in ultrafine particles (UFPs). UFPs represent a distinct toxicity concern because they can more easily evade the human body's respiratory filtering mechanisms and intrude the alveoli (Mühlfeld 2008). Within the alveoli, the UFPs can pass through the epithelial barrier, reach the connective tissue of the septa, traverse the cellular lining of the capillary blood vessels, and enter the circulatory system. Once in the blood stream, chemical components can reach every organ. As such, UFPs are transport platforms for adsorbed SOF carcinogenic components.

Table 2. UFP impact of emission controls

Lab Engine Configuration	Test Point	Total PM Concentration (#/cm^3)	Total UFP* Concentration (#/cm^3)	UFP Fraction
Baseline engine Baseline fuel (F-76)	TP1	13,972,000	13,904,000	99.5%
	TP9	16,745,000	16,677,000	99.6%
CCTS engine Baseline fuel (F-76)	TP1	13,774,000	13,724,000	99.6%
	TP9	12,200,000	12,166,000	99.6%
CCTS engine & Rypos AT Baseline fuel (F-76)	TP1	1,390,600	1,370,400	98.6%
	TP9	3,690,000	3,674,800	99.7%

*NOTE: Ultrafine particles (<100 nm geometric mean diameter)

The OC and EC results for the collected particulate matter for each of the five fuel types and engine operating conditions are displayed in Fig. 10. For each fuel type, the OC/EC fractions were lowest for the two conditions where the engine load was highest, TP1 and TP6. The combustion and exhaust temperatures at these two conditions were much higher than at TP5 and TP9. The higher combustion and exhaust temperatures result in more complete combustion and therefore a reduced OC fraction. The combustion and exhaust temperatures at idle were the lowest since no load was applied to the engine. Subsequently, this condition produced the highest OC fraction for each test condition. TP9 temperatures were still relatively low, but higher than at idle. As a result, the OC/EC ratio is higher than the two high load conditions, but less than that observed for idle. Interestingly, the F-76 fuel produced a lower OC/EC ratio than the other fuels at idle. The reason for this low result is unclear, however the F-76 combustion temperatures were likely somewhat higher than for the other fuel types.
All of the test fuels, except B20, produced similar TP9 OC/EC values. There was a noticeable increase in the OC/EC ratio of the B20 fuel, composed of ULSD and 20% biodiesel, when compared to DECSE ULSD. The biodiesel methyl esters have a much lower volatility than their diesel counterparts of the same carbon chain length. Therefore, the biodiesel chains are likely to remain in the particle phase at the lower combustion temperatures favoring OC.

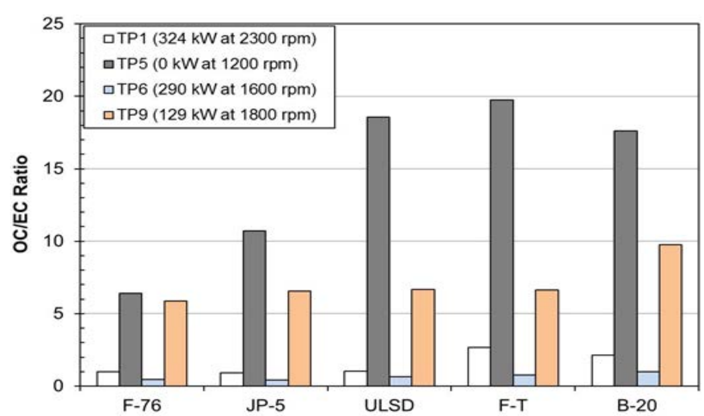

Fig. 10 OC/EC ratio for five fuels and four engine test points

The particulate matter was further analyzed according to its insoluble, sulfate, and soluble organic fractions (Fig. 11).

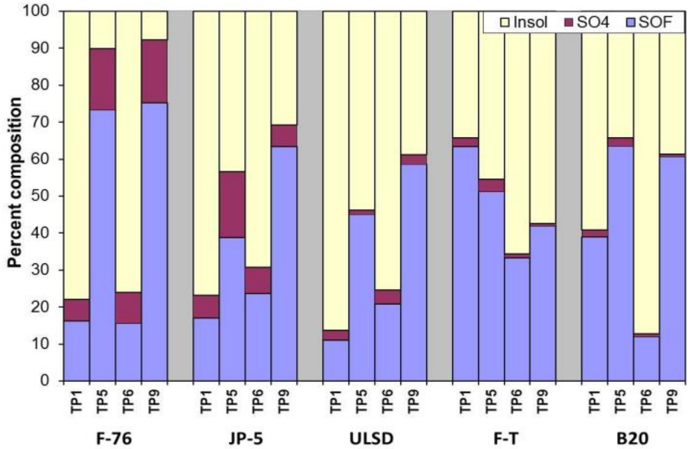

Fig. 11 Insoluble, sulfate, and soluble organic PM fractions of the five fuels at the four engine test points

The SOF was highest for TP5 and TP9, in agreement with the OC results (Fig. 10). Not surprisingly, the sulfate (SO_4) contents were extremely low for the F-T, DECSE ULSD, and B20 test fuels. These three fuels are produced from either natural gas (F-T) or refinery streams that no longer contain sulfur (DECSE ULSD and B20). Therefore, these fuels do not contain the sulfur normally present in middle distillate fuels. The other two test fuels, F-76 and JP-5, are middle distillate streams and, as a result, contain appreciable quantities of sulfur. The PM sulfate content was highest under the high load conditions; fuel sulfur is mainly emitted as SO_2 and higher temperatures enable further oxidation to sulfate. Since sulfates serve as precursors to UFP formation, their presence often corresponds to higher numbers of the smallest particles formed in the exhaust.

OC/EC, SOF, sulfate, and insoluble PM fractions of the alternative fuels indicate that the PM emissions generated by low sulfur test fuels would respond well to oxidative AT, such as a diesel oxidation catalyst (DOC), particularly at lower loads.

The brake-specific formaldehyde emissions are displayed for both D2 and E5 cycles in Fig. 12. The DNPH method also detected other aldehydes in significant quantities, including acetaldehyde, acrolein, and benzaldehyde.

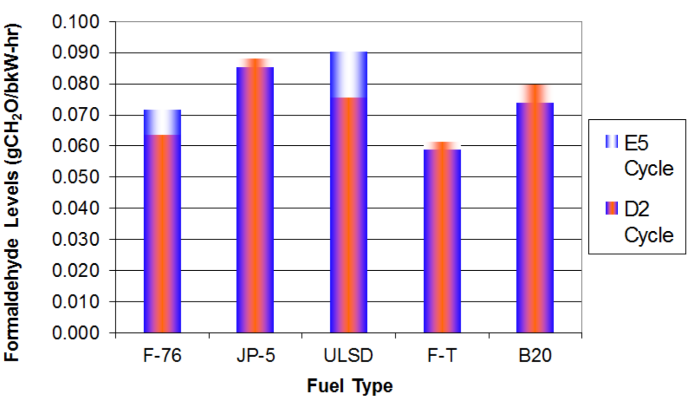

Fig. 12 Brake-specific formaldehyde emissions

Formaldehyde concentration is greatest by a factor of two or more. There are no large differences between the fuels, since aldehyde formation is more dependent on combustion conditions than fuel chemistry. These results correspond well to a study (McGill 2003) utilizing a medium-duty truck diesel 4S fueled with 350 ppm sulfur on-road diesel and biodiesel blends. That work exhibited similar formaldehyde emissions of 0.02 – 0.08 g/bkW-hr for a variety of steady-state speeds and loads. Similar small differences were evident for the biodiesel blends.

SHIPBOARD TEST PHASE

Following the laboratory testing, two COTS emission control technologies were considered for shipboard testing: the CCTS in-cylinder EGR and Rypos ERADPF. CCTS combines in-cylinder valve and injector timing changes with turborcharging the base naturally aspirated engine in order to effect internal exhaust gas recirculation (EGR) and thereby reduce NO_x emissions. The Rypos ERADPF traps and incinerates collected PM. Regeneration is triggered by achieving a pressure drop threshold. Although, a case could have been made for the Catane fuel additive to warrant additional testing, the logistical challenges of introducing a fuel additive on even a selective basis to obtain the modest emissions control results were difficult to justify from completed testing. Alternatively, the CCTS and Rypos controls presented what seemed to be a potentially cost-effective combination for NO_x and PM control.

Both technologies exhibited some problems when laboratory tested, but on-site and subsequent OEM fault identification investigations indicated that these could be corrected and did not indicate fundamental design flaws. Therefore, preparations were made to install both control technologies on a test vessel for baseline, 1-year early degradation, and late-life tests.

Test Vessel Modification

Installation of both technologies required more than simple component replacement. Thus sufficient availability of the test vessel was required for conducting both modifications and on-the-water testing.

Selection of the test vessel targeted vessels that were powered by the same engine model as that tested in the laboratory. The test vessel needed to be accessible and in high operating hour service. A former twin-screw Navy Seaplane Wrecking Derrick (YSD) self-propelled barge crane was identified as an ideal candidate. The YSD was in daily use ferrying workers and equipment to and from the National Defense Reserve Fleet (NDRF) (Suisun Bay, CA). This vessel was also powered by two DDC 12V-71N engines – representative of the engines in the NPECP-selected legacy engine subset. The MARAD program director recognized a need to reduce emissions of the workboat fleet and partnered with NAVSSES to complete the shipboard performance, reliability, and durability portions of the NPECP program. In 2013, MARAD informed NAVSSES that the YSD would be undergoing a major drydock service life extension overhaul in 2014. The final T3 shipboard test was conducted just prior to that drydocking (Table 3).

Table 3. Shipboard tests

Shipboard Test	Test Description	Test Dates	Accumulated Operating Hours*
T1	Baseline	Jan 2006	130
T2	1-year early-degradation	Nov 2006	1,010
T3	9-year late-life	Nov 2014	9,512

*NOTE: Port engine hours

Installation of the refurbished lab test engine with COTS CCTS components was conducted, replacing the port main propulsion diesel engine (MPDE). The port engine exhaust piping was altered to accommodate two COTS Rypos ERADPFs (RT24-2C). A single customized Rypos unit could have been used, but the COTS units were required by the project schedule and budget. The most straightforward and lowest cost CCTS and Rypos installations would involve an in-place replacement of stock engine components with those from the CCTS kit and a muffler or silencer with a Rypos ERADPF system.

The CCTS modified engine introduced in-cylinder NO_x control by effecting internal EGR, and the ERADPF provided AT PM filtering. The two technologies together were expected to significantly reduce NO_x and PM from one of the two YSD MPDEs. The starboard MPDE would be maintained in its original configuration as a baseline reference engine. Shipboard back-to-back performance test data could then be compared. Both engines were set up to develop 317 kW at 2300 rpm (previous engines in this craft were derated).

The YSD lazarette space was dimensioned (Fig. 13) and exhaust piping configuration changes were modeled (Figs. 14 and 15) to identify a retrofit design that could accommodate the Rypos ERADPFs. Restriction calculations were made to determine if the piping configuration could meet the engine back pressure specification for the operating envelope's exhaust flow range.

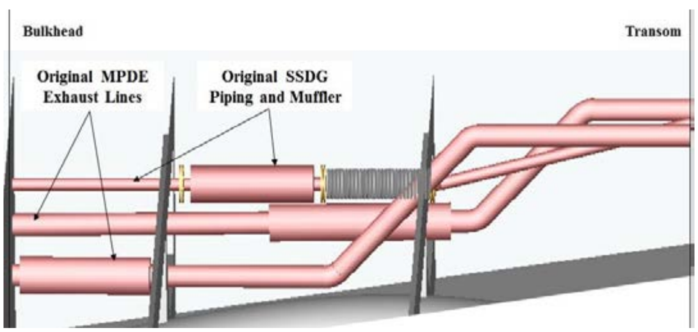

Fig. 13 YSD MPDE original lazarette exhaust layout

Left and right bank pipes were joined aft of the lazarette bulkhead penetration (Fig. 14). The pipe was split before directing the exhaust stream into the twin ERADPFs (Fig. 15). The dual pipes exiting the ERADPFs were again joined into a single pipe. An aft deck penetration was made to accommodate the single pipe riser, upstream of the transom exit port (Fig. 14). The riser would prevent ingestion of raw water into the ERADPFs during adverse current or sea state conditions.

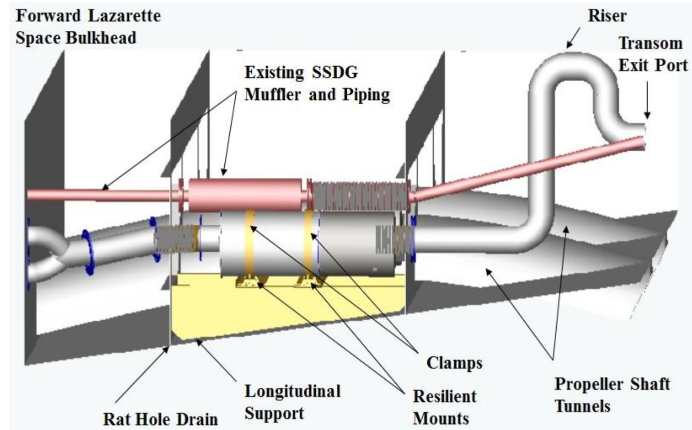

Fig. 14 MPDE modified ERADPF exhaust layout

Possible exhaust pipe configurations did not accommodate ISO 8178's requirement of ten pipe diameters upstream and three pipe diameters downstream of the exhaust sampling probes; however, the probe locations were selected to ensure well mixed flow and as little flow disturbance as possible.

Via an aft deck soft patch, the ERADPFs were resiliently mounted in the lazarette space; sampling probe, thermocouple, and pressure transducer access ports were constructed; ERADPF control panel and alarms were installed; and three-phase power was run to the control panel and ERADPFs.

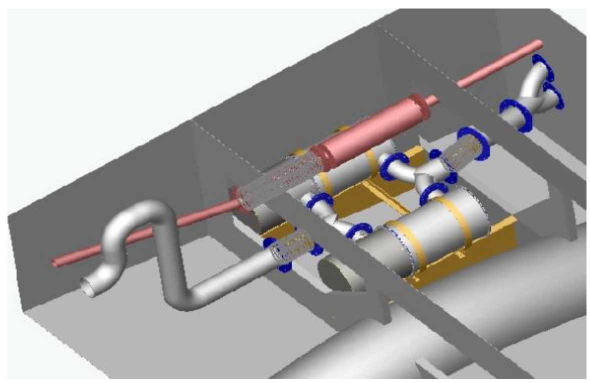

Fig. 15 MPDE modified ERADPF exhaust layout (isometric)

Vendor Memorandums of Understanding were developed with technology suppliers to ensure adequate support over the useful life of changed out components and new systems.

Procedure

Table 3 shipboard tests T1-T3 were conducted with the vessel underway in open water near to the NDRF (Suisun Bay, CA). In tests T1 and T2 (January and November 2006) the emissions were measured from the modified port engine and the unmodified starboard engine. For test T3 (November 2014) emissions were only measured from the port engine because the starboard engine had been replaced. The test points were set while the test vessel was underway. Engines were operated as close as possible to each operating mode prescribed by ISO 8178 protocol, E5 test cycle (Table 4) (Behr 2003).

Table 4. Shipboard test matrix

Cycle	Mode	Test Point	Rpm (%RS)	Load (%FL)	Rpm (actual)	BkW (actual)	ISO 8178 WF*
E5	1	1	100	100	2300	317	0.08
	2	2	91	75	2093	238	0.13
	3	3	80	50	1840	159	0.17
	4	4	63	25	1449	79	0.32
	5	5	idle	0	1200	0	0.30

*NOTE: Weighting factor

The fuel used in Suisun Bay's workboat fleet is an F-76/MGO mixture scavenged from the NDRF (analysis results for each shipboard test period in Appendix B). Fuel sulfur levels were similar to that of the F-76 laboratory test fuel.

ISO 8178 cycle E5 (Table 4) was followed as closely as possible. The test sequence is conducted as follows:

- The engine is run at rated speed and full power to warm up and stabilize emissions for thirty minutes.
- A plot or map of the peak power as a function of engine speed is determined for the port and starboard engines, starting with rated speed. Because the 100% load point at rated speed was unattainable with the propeller operating torque, Mode 1 was chosen to represent the highest attainable rpm and load.
- Emissions are measured while the engine operates according to the parameters of ISO-8178, E5 test cycle. Mode 1 is run first; with the highest achievable load determined by the engine map.
- After Mode 1, each mode is run in sequence. The minimum run time is ten minutes; it is extended at some mode points to collect sufficient particulate sample mass. The modal time period is recorded and reported.
- The gaseous exhaust emission concentration of CO, CO_2, and NO_x, are measured and recorded for the last three minutes of each mode. The completion of particulate sampling is coincident with the completion of the gaseous emission measurements.
- Engine speed, boost pressure, and intake manifold temperature are measured to calculate the gaseous flow rate at each mode. Engine speed is measured from an optical pickup installed on the engine driveshaft. Torque is measured with a driveshaft-mounted strain gauge.
- Emissions factors are calculated in terms of grams per kilowatt-hour for each of the operating modes and sampling locations tested, allowing for emissions comparisons between the baseline and controlled engines, as well as the individual performance of each of the two emission control technologies.
- Weighted emissions are calculated by Eq. 1.

$$EF_x = \frac{\sum_{i=1}^{i=n} m_i WF_i}{\sum_{i=1}^{i=n} p_i WF_i} \qquad (1)$$

Where EF_x is the weighted mass emission level in g/kW-hr of each pollutant and m_i (g/hr), WF_i, and p_i are the mass emission rate, weighting factor, and engine load, respectively, for the "i"-th operating mode. Because mode 1 was not achievable in practice, mode 2 was assigned a WF of 0.21.

Criteria Pollutants measurement was conducted by the University of California, Riverside (UCR).

Activity Tracking data was collected in September 2006. UCR installed temperature and pressure sensors upstream and downstream of the port engine ERADPFs.

Instrumentation

Engine Measurements consisted of fuel flow, engine air flow, and torque. The following pressures were also measured: lube oil, air box, left and right bank exhaust manifold and ERADPF delta P. Temperature measurements included: inlet air, cooling system water, and exhaust manifold left and right bank.

Fuel Consumption is the difference between the fuel supply and return flow. Three separate shipboard tests were performed. In Tests 1 and 2, fuel flow was measured by two Rosemount Micro Motion Coriolis flow meters. The analog output from each meter was recorded by the data acquisition system (DAS) and the difference computed post-test. In Test 3, two Kral OME20 Flow meters in combination with a Kral BEM-500 were used. The BEM-500 controller was configured to subtract the return flow meter signal from the supply signal and produce an analog output to the DAS proportional to fuel consumption.

Intake Air Flow rate was measured by means of a Rosemount Annubar 485 flowmeter element mounted in an 8" diameter Aluminum tube. Differential pressure (impact less static) from the Annubar was measured with a delta-p pressure transducer. A K type thermocouple probe provided the analog temperature output. Data were recorded by the DAS. The combination of the pressure delta and inlet temperature and constants specific to the flowmeter produced a pressure versus flow curve, which was computed post-test.

Torque was measured by a full bridge strain gage bonded to the propeller shaft. The strain signal was conditioned and transmitted wirelessly to a receiver which produced an analog output signal recorded by the DAS. A strain to torque conversion was computed using the characteristics of the electronic system and shaft material and geometry. A Binsfeld Engineering Torquetrak 9000 system was used for T1 and T2, and a Lord Microstrain system for T3.

DAS systems utilized for T1 and T2 was an Iotech Dacbook and for T3 was a Dataforth DAQ-20. A laptop computer acquired the data produced by each DAS.

Emission Measurements were made with a Horiba PG-250 portable multi-gas analyzer. The PG-250 can simultaneously measure up to five separate gas components using the measurement methods recommended by the EPA. The signal output of the instrument is interfaced directly with a laptop computer through an RS-232C interface to record measured values continuously. Major features include a built-in sample conditioning system with sample pump, filters, and a thermoelectric cooler. The performance of the PG-250 was tested and verified under the U.S. EPA ETV program.

Details of the gases and the ranges for the PG-250 instrument are shown in Table 5. Note that the PG-250 instrument measures sulfur oxides (SO_x); however, direct measurement of SO_2 is less precise than a concentration calculation from fuel sulfur analysis (ISO 1998).

Table 5. Detector method and concentration ranges for PG-250

Component	Detector	Ranges
Nitrogen Oxides (NO_x)	Heated Chemiluminescence Detector (HCLD)	0-25, 50, 100, 250, 500, 1000, and 2500 ppmv
Carbon Monoxide (CO)	Non Dispersive Infrared Adsorption (NDIR)	0-200, 500, 1000, 2000, and 5000 ppmv
Carbon Dioxide (CO_2)	Non Dispersive Infrared Adsorption (NDIR)	0-5, 10, and 20 vol%
Sulfur Dioxide (SO_2)	Non Dispersive Infrared Adsorption (NDIR)	0-200, 500, 1000, and 3000 ppmv
Oxygen (O_2)	Zirconium Oxide Sensor	0-5, 10, and 25 vol%

UCR methods for sampling and analysis of the gases and PM from harbor craft vessels conform to the requirements of ISO 8178-1. The approach involves the use of a partial flow dilution system with single Venturi (VN) (Fig. 16). The VN negative pressure created by dilution tunnel (DT) draws the raw exhaust gas from the exhaust pipe (EP) to the DT through the sampling probe (SP) and the transfer tube (TT). The transfer line is heated to prevent condensation of exhaust components (including water and sulfuric acid) at any point in the sampling and analytical systems. Heated transfer lines (15 ft. in length) were used to convey raw exhaust samples to the dilution sampler location. The PG-250 exhaust gas analyzer draws gas samples from DT, while the PM is drawn through a cyclone to first size particles to 2.5 µm. The sample is then split to collect PM on a Teflon filter for total weight measurement and on a quartz filter for subsequent analysis of OC and EC.

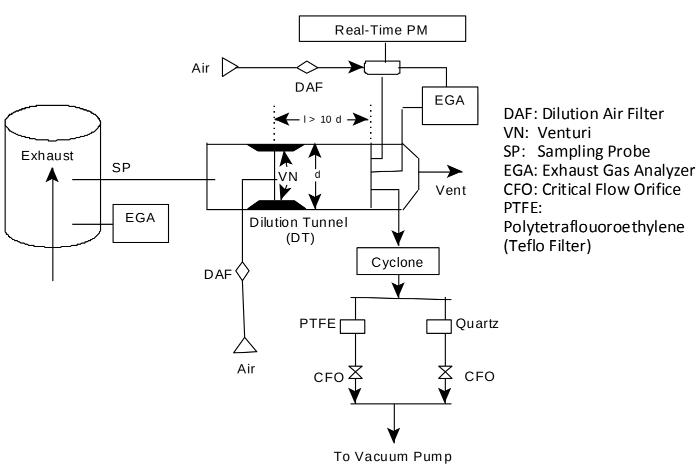

Fig. 16 Partial flow dilution system with single venturi, concentration measurement, and fractional sampling

In addition to the filter-based PM mass measurements, UCR took continuous readings with a Nephelometer (TSI DustTrak 8520) measuring 90º light scattering at 780 nm to see PM qualitatively in real time. The DustTrak is a portable, battery-operated laser photometer that gives real-time digital readout with the added benefits of a built-in data logger. The unit is fairly simple to use and has excellent sensitivity to untreated diesel exhaust. This instrument measures light scattered by aerosol introduced into a sample chamber. The measured mass density is displayed in units of mg/m^3.

Results

The T1-T3 shipboard tests (conducted in January 2006, November 2006, and November 2014 [Table 3]) weighted emission results for the uncontrolled starboard engine and upstream and downstream of the port engine ERADPF are presented in Figs. 17-20. Fuel consumption and the OC/EC ratio results are displayed in Fig. 21 and Fig. 22, respectively. The data range for each mode is indicated by a bar. Note that in Fig. 17, the starboard emissions are divided by two and in Fig. 19 they are divided by three.

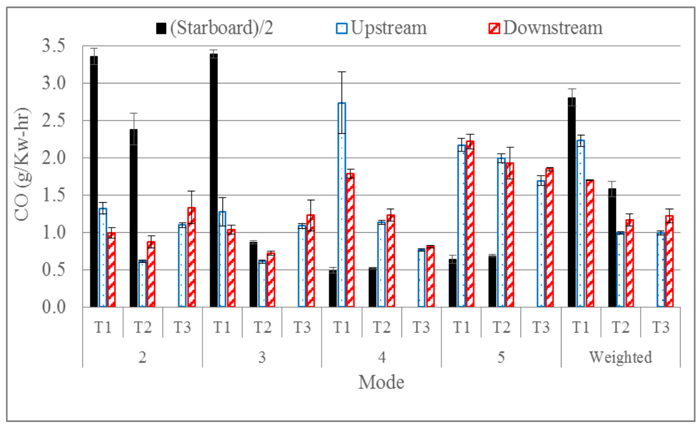

Fig. 17 Brake-specific CO emissions

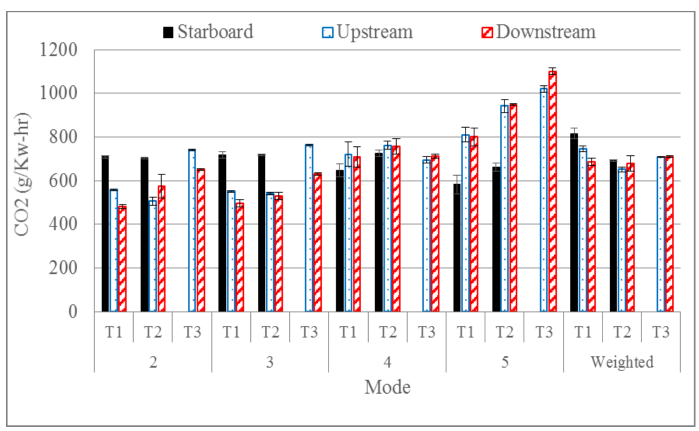

Fig. 18 Brake-specific CO_2 emissions

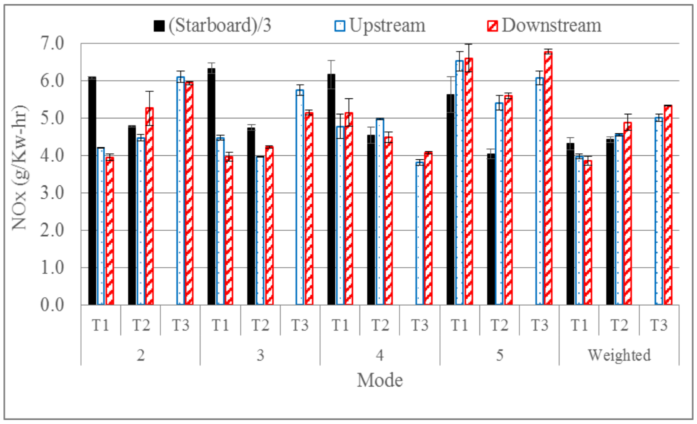

Fig. 19 Brake-specific NO_x emissions

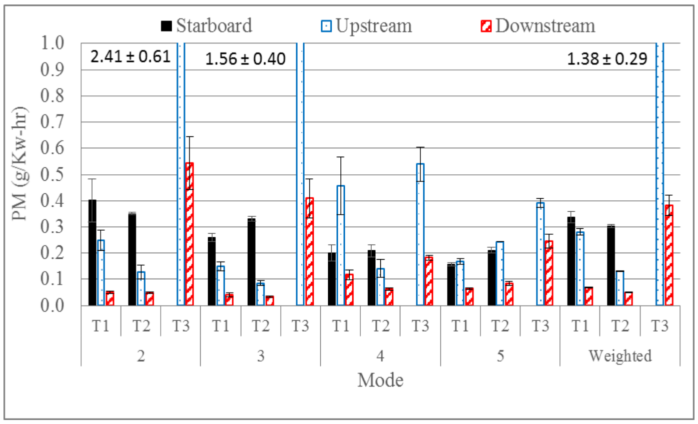

Fig. 20 Brake-specific PM emissions

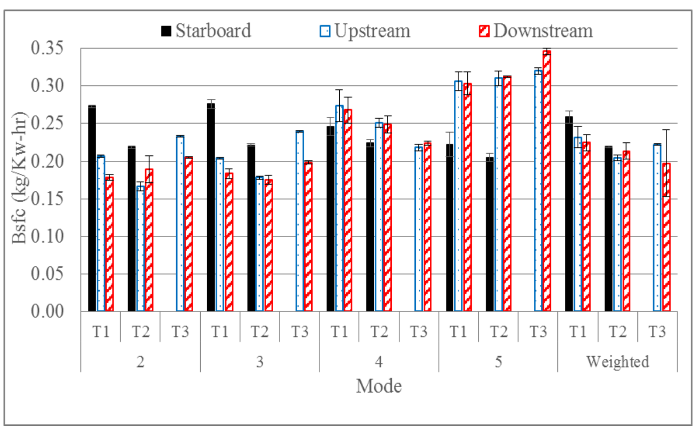

Fig. 21 Brake-specific fuel consumption

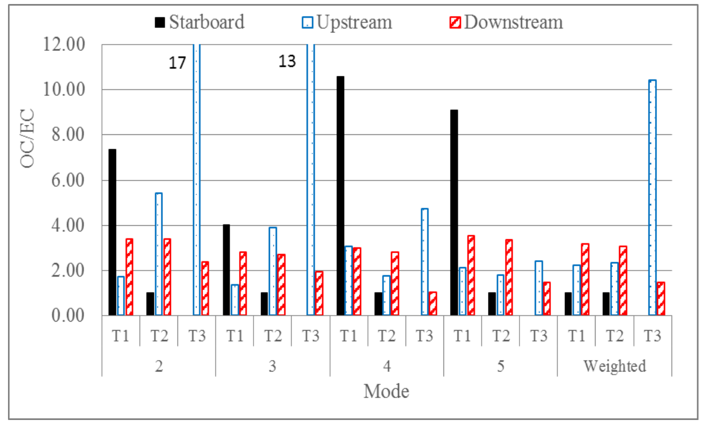

Fig. 22 OC/EC ratio

If all test conditions were exactly the same, then the CO_2 emissions and the fuel consumption upstream and downstream of the port engine ERADPFs should be exactly the same at each mode and for the weighted results. The downstream emissions were measured while the YSD traveled toward the San Francisco Bay and the upstream measured during the return. The differences observed may be related to changes in speed and direction of ocean and wind currents relative to the YSD.

The percent reduction of the port engine emissions relative to the starboard engine emissions for the upstream and downstream cases is presented in Figs. 23 and 24, respectively. When port engine emissions are higher than those of the starboard engine, there are no bars. Based on the weighted downstream data, the port engine NO_x emissions were 70%, 63%, and 59% lower than the starboard engine for tests T1, T2, and T3, respectively. For CO the percentages were lower by 70%, 63%, and 72%, respectively. While these percentages indicate some loss in emission control efficiency for NO_x, and mixed results for CO, the lower CO_2 equivalent percentage values (16%, 2%, and 6%, respectively) indicate that this possible efficiency loss should not be overly emphasized.

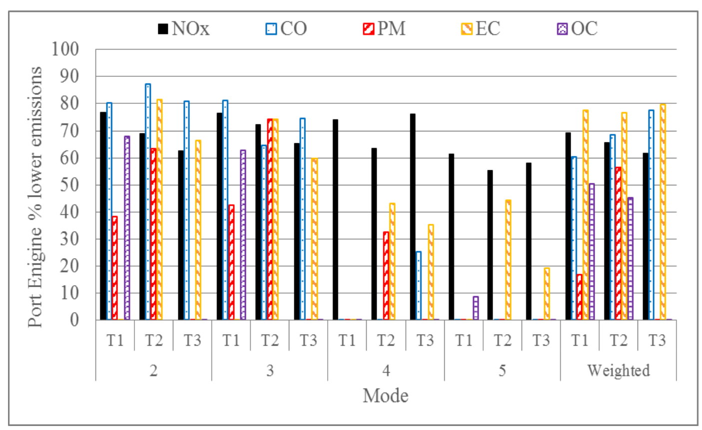

Fig. 23 Port engine upstream emissions – percentage reduction compared to starboard engine

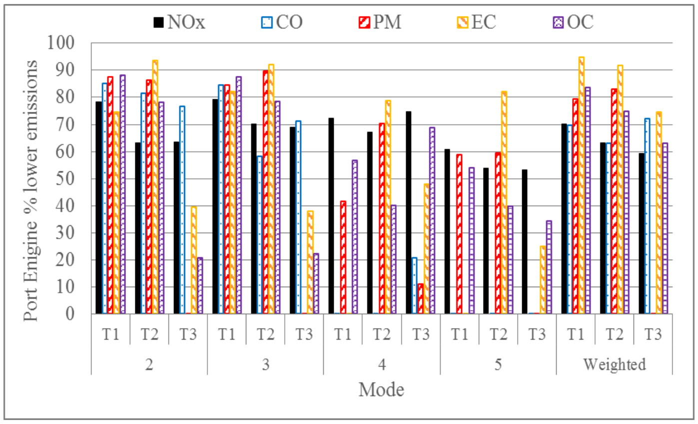

Fig. 24 Port engine downstream emissions – percentage reduction compared to starboard engine

The percent reduction of PM, EC, and OC mass across the ERADPF is presented in Fig. 25. When downstream emissions are higher than the upstream emissions (only occurs for test T3), there are no bars. The respective changes for tests T1-T3 are as follows: on a weighted basis the percent efficiency of the ERADPF for total PM was 75%, 61%, and 72%; for OC was 67%, 54%, and 83%; and for EC was 77%, 65%, and -25%. During test T3, the port engine showed an unexplained increase in engine-out PM, OC, and EC emissions relative to tests T1 and T2. The PM percent efficiencies are approximately the same for T1, T2, and T3, but the OC and EC percent efficiencies for T3 are not similar to T1 and T2. The T3 modal PM upstream and downstream values were ~1.1 to 10 times higher than the equivalent modal T1 and T2 upstream and downstream PM values. The T3 upstream EC was 0.8 to 1.3 times higher, while the downstream T3 EC was 2.2 to 9.4 times higher. The upstream T3 OC was 1.1 to 9.5 times higher and the downstream T3 OC was 0.5 to 6.6 times higher. Some of the particulate filters had a whitish substance on them which was assumed to be ash flaking off the ERADPFs. This ash shedding might explain the higher ratios for the downstream EC versus the upstream EC. The OC-EC measurement method would classify any ash flaking off the ERADPFs as EC.

The engines are equipped with Walker breather systems; breather pipes on each side of the engine ventilate the crankcase of the engine. Each pipe feeds into a connector at the base of an air filter designed to remove oil before the ventilated mixture gets mixed with the intake air to the engine. Both filters were dripping with oil prior to T3. They were removed, the housing cleaned out, and new filters installed. From the time of emission controls installation and T3 (9,512 hours), the engine Walker breather system was not well maintained and the ERADPFs did not receive any prescribed annual ash inspections. The neglect of one or both maintenance measures may have contributed to increased engine lube oil ingestion and ERADPF ash shedding. Increasing sump pressure from worn piston ring "blow-by" could also have contributed to lube oil ingestion. Alternatively, the lube oil ingestion may have caused an increase in blow-by, by exacerbating the formation of more in-cylinder PM and deposits. The schedule for removal of the YSD from service did not afford time for engine cylinder inspection or further investigation. Therefore, it was not possible to discern which effect/s might be the primary cause of PM increase.

An OEM teardown of the ERADPFs indicated that the 67% active (electrically regenerated) and 33% passive system degraded functionally to a predominantly passive system. Nevertheless, total ERADPF PM filtering efficiency actually improved when measured at T3 compared to that of early-life (T1 and T2 average). ERADPF sulfur tolerance was also maintained.

Rypos has upgraded the ERADPF electronics, substantially improving the reliability of the systems' electronic control units (ECUs). The over-voltage protection circuit now has an increased margin for absorbing transient high voltages that may have caused the observed degradation. CARB has reviewed and approved the design changes and the upgraded systems have been performing successfully.

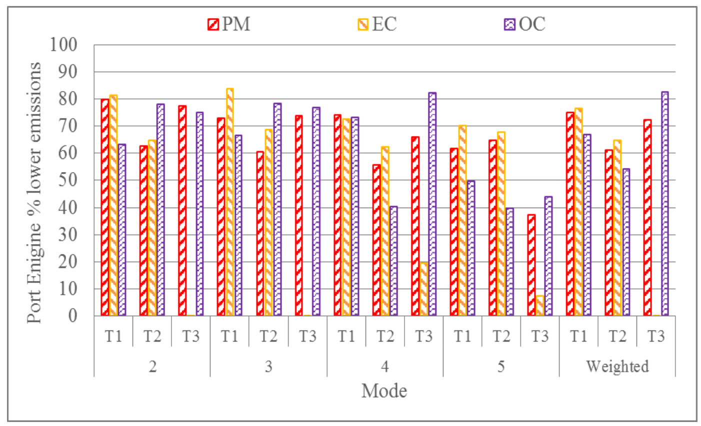

Fig. 25 Port engine ERADPF emissions – percentage reductions across units

A qualitative estimate of sulfur dioxide (SO_2) emissions is presented in Fig. 26. As noted previously, the PG-250 measures SO_2 but the measurement is not considered as accurate as an emissions calculation based on the sulfur content of the fuel. The sulfur content was approximately the same for all the fuels used for each shipboard test (Appendix 2). The calibration mixtures used to calibrate the PG-250 contain only CO, NO_x, and CO_2. The Fig. 26 emissions of SO_2 were calculated by assuming the PG-250 SO_2 readings are the actual SO_2 concentrations in ppmv. As seen in Fig. 20 for tests T1 and T2, the SO_2 emissions are approximately the same for the starboard and the port engine while the T3 results are generally higher. This may indicate that oil is getting into the combustion chamber.

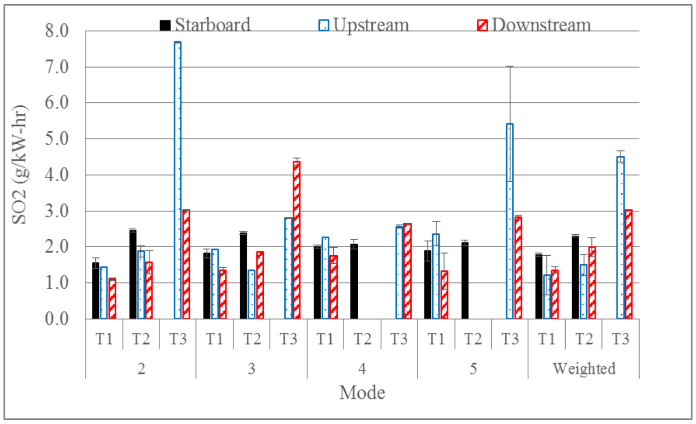

Fig. 26 Estimated brake-specific SO_2 emissions

Beginning on Sepetember 5, 2006 the activity was tracked for nine weeks. The tracking consisted of measuring the pressure and temperature upstream and downstream of the port engine ERADPFs. No significant differences were observed between the upstream and downstream temperatures or pressures.

CONCLUSIONS

Lab Test Phase

A published solicitation yielded thirteen prospective emission control technologies that could be applied to the selected subset of ~1,040 U.S. Navy high fuel-consuming and fuel-polluting 2S high-speed marine diesel engines (~50% naturally aspirated [NA]). Five of the thirteen controls were determined to possess a sufficiently high rating for operation within representative Navy operating conditions to justify a laboratory screening test at NAVSSES. Two of the five controls were eliminated during lab testing based on necessary development or vendor support. Of the three remaining technologies under investigation, two demonstrated sufficient potential to be selected for a follow-on shipboard performance, reliability, and durability test.

- Of the alternative fuels considered for emission control, all fuels tested as alternatives to F-76 exhibited one or more beneficial NO_x, PM, or bsfc reduction relative to the F-76 baseline. Only ULSD and F-T resulted in significant E5 cycle NO_x reductions (11% and 4%, respectively); JP-5, ULSD, F-T, and B20 all produced significant PM reductions (48%, 33%, 13%, and 22%, respectively); and ULSD and F-T resulted in significant bsfc improvements (5% and 6%, respectively).
- With the engine modified to the CCTS configuration, all successfully tested emission control technology combinations significantly reduced NO_x. The CCTS control individually produced a significant PM increase, but when fueled with one of the alternative fuels, the CCTS configured engine achieved a significant PM reduction (40% and 38% for JP-5 and ULSD, respectively). Without using an alternative fuel, CCTS and Rypos controls combined offered 55%, 50%, and 3% reductions of NO_x, PM, and bsfc, respectively.
- PM size and number concentration data indicate that while the NO_x-optimized CCTS substantially increases PM, the Rypos ERADPF exhibits effective AT filtering, decreasing PM number concentration and mass by 90% and 64% (TP1 [100% load]) and by 70% and 45% (TP9 [50% load]), respectively. From the F-76 baseline the Rypos ERADPF reduces TP1 PM number and mass by 90% and 32%, and TP9 by 78% and 57%, respectively. UFPs are reduced in proportion to the total PM reduction.
- OC/EC, SOF, sulfate, and insoluble PM fractions of the alternative fuels indicate that the PM emissions generated by low sulfur test fuels would respond well to DOC oxidative AT, particularly at lower loads.

Shipboard Test Phase

The two control technologies selected for testing in an operating vessel on the water, required significant installation work on the test vessel. One of two MPDEs was replaced with the COTS CCTS-modified engine and its exhaust piping system was partially reconfigured to accommodate two COTS Rypos ERADPFs. After the modified engine was broken in, both engines were instrumented and tested three times (T1-T3).

- T1-T3 weighted data indicated NO_x reductions of 70%, 63%, and 59%, respectively, compared to the baseline starboard engine.
- T1-T3 weighted ERADPF percent efficiency was 75%, 61%, and 72% for total PM; 67%, 54%, and 83% for OC; and 77%, 65%, and -25% for EC.
- T3 modal PM upstream and downstream values were 1.1 to 10 times higher than equivalent T1 and T2 upstream and downstream PM values. This could be attributed to increased lube oil ingestion from a poorly maintained breather system and/or increased cylinder blow-by.
- T3 emission results, measured after nine years and 9,512 hours of operation, indicate emission controls are performing at 11% degraded efficiency for NO_x and 6% improved efficiency for total PM compared to early in the life of the controls (T1 and T2 average). The ERADPF sulfur tolerance appeared to be maintained.

RECOMMENDATIONS

JP-5, ULSD, and F-T alternative fuels and the combination of CCTS internal EGR and Rypos ERADPF AT provided significant emission reductions and demonstrated reliable emission control with high performance and durability. Improved engine maintenance would be expected to improve CCTS and Rypos ERADPF performance and useful life.

The emission control systems (PM- or NO_x-optimized CCTS and DOC-equipped Rypos ERADPF) in tandem or individually are recommended for Navy application where cost effective and as approved by the equipment Technical Warrant Holders.

The Navy should develop a robust cost/benefit analysis standard procedure to assess the value of specifying new engines in commercial compliance and the benefits of selectively applying emission controls on engines already in operation. An existing broad cost/benefit assessment methodology, applicable to all the Services, should be further refined and validated.

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Appendix 1. Lab Testing Fuels Analyses

Date of Test Reports: 9 Aug 2004

Characteristic	F-76 Requirement	ASTM Test Method	F-76 (lab test)*	JP-5 (lab test)*	B20 (lab test)*	ULSD (lab test)*	F-T Synthetic (lab test)*
Acid Number	0.30 mg KOH/g max	D 974	0.060	0.005	0.030	0.000	0.005
Appearance @ 25 °C	Clear, bright and free of visible particulates	D 4176	Clear & bright	N/App	Clear & bright	Clear & bright	Clear & bright
Total Aromatics**	No spec. limit	D 6379 % wt.	26.2	22.00	16.2	24.1	N/App
Aromatics, Dicyclic**	No spec. limit	D 6379 % wt.	4.6	1.2	1.9	6.5	0.0
Aromatics, Monocyclic**	No spec. limit	D 6379 % wt.	21.6	20.8	14.3	17.6	0.0
Ash	0.005 wt% max	D 482	<0.001	N/App	< 0.001	< 0.001	< 0.001
Carbon Residue (Ramsbottom 10% bottoms)	0.20 wt% max	D 524	0.14	N/App	0.07	0.08	0.01
Cetane Index	43 min	D 976	50.5	46	42.4	53.7	77.2
Cloud Point	-1 °C max	D 2500	-11.1	N/App	-26.9	-22	-2.2
Color max	3 max	D 1500	2.3	N/App	0.5	1.6	0.0
Corrosion @ 100 °C	No. 1 max	D 130	1a	N/App	1a	1a	1a
Demulsification @ 25 °C	10 minutes max	D 1401	7	N/App	9	2	3
Density @ 15 °C	876 kg/m^3 max	D 4052	842.4	803.9	831.5	825.8	782.8
Distillation Initial Boiling Point		D 86	186.0	178.5	175.0	183.5	233.3
10% Point	Record		217.0	189.5	191.0	206.5	260.0
50% Point	Record		270.5	207.5	226.0	259.0	291.5
90% Point	357 °C max		326.5	235.5	326.5	311.0	324.5
End Point	385 °C max		355.5	255.0	342.5	349.5	337.5
Residue + Loss	3.0 % volume max		1.5	1.0	1.2	1.5	1.9
Flash Point	60 °C min	D 93	69.0	65.5	61.5	72	105.5
Heating Value **	No spec. limit	D 4809 Btu/lb	18,374	18,546	18,162	18,464	18,906
Hydrogen Content	12.5 wt% min	D 3701	13.61	14.29	13.73	14.29	15.553
Lubricity – BOCLE** (wear scar dia. [mm])	No spec. limit	D 5001	-Not Run-	0.566	0.508	0.601	0.624
Lubricity SLBOCLE** (scuffing load [g])	No spec. limit	D 6078	-Not Run-	1875	4,750	2,500	2,100
Naphthalenes**	No spec. limit	D 1840 % wt.	6.9	N/App	1.8	1.3	0.0
Particulates	10 mg/L max	D 6217	0.90	0.90	3.5	0.08	0.000
Pour Point	-6 °C max	D 5985	-18	N/App	-54	-27	-3
Storage Stability	3.0 mg/100 mL max	D 5304	2.50	N/App	200	0.85	-0.75
Sulfur Content	1.0 % wt. max	D 4294 % wt.	0.572	0.138	0.008	0.007	0.005
Thermal Stability**	180 min.; 70% min 90 min.; 70% min	D 6468 % reflectance	45.70 19.70	N/App	99.3 99.6	98.0 98.2	99.7 99.7
Trace Metals - Calcium	1.0 ppm max	In-house method	0.036	N/App	0.143	0.67	0.010
Trace Metals - Lead	0.5 ppm max	In-house method	<0.037	N/App	<0.037	<0.037	<0.037
Trace Metals - Sodium + Potassium	1.0 ppm max	In-house method	0.140	N/App	0.23	0.1220	<0.013
Trace Metals - Vanadium	0.5 ppm max	In-house method	0.022	N/App	0.006	0.012	0.014
Viscosity @ 40 °C	1.7 – 4.3 cSt	D 445	2.721	1.362	1.83	2.384	3.337

*NOTE: Tests conducted by NAVAIR (AIR 4.4.5)
**NOTE: Report only – not a specification requirement

Appendix 2. Shipboard Testing Fuels Analyses

Dates of Test Reports: 9 Aug 2004, 3 Mar 2006, 16 Apr 2007, and 20 Nov 2014

Characteristic	F-76 Requirement	ASTM Test Method	F-76 (lab test)*	F-76/MGO (shipboard test)*	F-76/MGO (shipboard test)*	F-76/MGO (shipboard test)**
Acid Number	0.30 mg KOH/g max	D 974	0.060	0.0391 / 0.0442	0.05	0.06
Appearance @ 25 °C	Clear, bright and free of visible particulates	D 4176	Clear & bright	Clear & bright; vis. part. (fail)	Clear & bright, no vis. part.	Clear & bright (fail), vis. part. (fail)
Total Aromatics***	No spec. limit	D 6379 % wt.	26.2	47.34	42.3	37.13
Aromatics, Dicyclic***	No spec. limit	D 6379 % wt.	4.6	16.32	15.7	18.06
Aromatics, Monocyclic***	No spec. limit	D 6379 % wt.	21.6	31.02	26.6	19.1
Ash	0.005 wt% max	D 482	<0.001	< 0.001	< 0.001	0.003
Carbon Residue (Ramsbottom 10% bottoms)	0.20 wt% max	D 524	0.14	0.27	0.28	0.06
Cetane Index	43 min	D 976	50.5	48.8	47.7	46.5
Cloud Point	-1 °C max	D 2500	-11.1	-5.2	-6	-3
Color max	3 max	D 1500	2.3	L 5.0	Red dye	L 6.0
Corrosion @ 100 °C	No. 1 max	D 130	1a	2c	2c	1a
Demulsification @ 25 °C	10 minutes max	D 1401	7	>30	>30	30
Density @ 15 °C	876 kg/m^3 max	D 4052	842.4	857.4	861	866
Distillation Initial Boiling Point		D 86	186.0	201.0	200.5	200.3
10% Point	Record		217.0	234.0	236.5	222.0
50% Point	Record		270.5	287.0	287.5	288.2
90% Point	357 °C max		326.5	339.5	337.5	339.0
End Point	385 °C max		355.5	362.5	360.0	360.5
Residue + Loss	3.0 % volume max		1.5	1.6	1.6	2.0
Flash Point	60 °C min	D 93	69.0	63	84	80
Heating Value ***	No spec. limit	D 4809 Btu/lb	18,374	18,275	18,192	19,280
Hydrogen Content	12.5 wt% min	D 3701	13.61	12.989 / 12.897	12.7 (D7171)	12.74
Lubricity – BOCLE*** (wear scar dia. [mm])	No spec. limit	D 5001	-Not Run-	- Not Run -	0.615	- Not Run -
Lubricity SLBOCLE*** (scuffing load [g])	No spec. limit	D 6078	-Not Run-	- Not Run -	5,700	- Not Run -
Naphthalenes***	No spec. limit	D 1840 % wt.	6.9	12.48	13.9	>5
Particulates	10 mg/L max	D 6217	0.90	4.4	1.3	14.0
Pour Point	-6 °C max	D 5985	-18	-12	-3.8	-3.8
Storage Stability	3.0 mg/100 mL max	D 5304	2.50	2.75	2.75	-11
Sulfur Content	1.0 % wt. max	D 4294 % wt.	0.572	0.524 / 0.524	0.5	0.556
Thermal Stability***	180 minutes 90 minutes	D 6468 % reflectance	45.70 19.70	- Not Run -	35.4 53.1	- Not Run -
Trace Metals - Calcium	1.0 ppm max	In-house method	0.036	1.26	0.8	7.2
Trace Metals - Lead	0.5 ppm max	In-house method	<0.037	<0.057	<0.1	<0.4
Trace Metals - Sodium + Potassium	1.0 ppm max	In-house method	0.140	0.621	0.2	2.5-2.7
Trace Metals - Vanadium	0.5 ppm max	In-house method	0.022	0.021	0.1	<0.1
Viscosity @ 40 °C	1.7 – 4.3 cSt	D 445	2.721	3.38	3.42	3.49

*NOTE: Tests conducted by NAVAIR (AIR 4.4.5)
**NOTE: Tests conducted by SGS Herguth Laboratories (Vallejo, CA)
***NOTE: Report only – not a specification requirement