Costs of Emission Reduction Technologies for Category 3 Marine Engines

Final Report

United States
Environmental Protection
Agency

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Final Report

Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

Prepared for EPA by
ICF International
EPA Contract No. EP-C06094
Work Assignment No. WA1-8

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United States Environmental Protection Agency

EPA-420-R-09-008
May 2009

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1. Introduction

In December 2007, EPA published an Advanced Notice of Proposed Rulemaking to enact more stringent exhaust emission standards for engines on ocean going vessels.[1] New NOx and SOx exhaust emission standards were discussed for engines on Category 3 marine vessels.[2]

Two new tiers of NOx standards have recently been adopted by the IMO. Tier II NOx standards are roughly 20 percent lower than the existing Tier I NOx standards set by the International Maritime Organization in Annex VI.[3] To meet these standards, in-cylinder emission control approaches such as electronically controlled high pressure common rail fuel systems, turbocharger optimization, compression ratio changes and electronically controlled exhaust valves could be used. Tier III NOx standards which only apply in designated Emission Control Areas are roughly 80 percent below Tier I NOx standards and would likely require exhaust aftertreatment such as selective catalytic reduction (SCR). Other approaches that may be considered to reduce NOx emissions from Category 3 vessel engines are exhaust gas recirculation and water technologies such as direct water injection or fumigation.

In addition to these NOx standards for new Category 3 marine vessel engines, standards were adopted by the IMO for NOx limits for existing engines due to the very long life of ocean going vessels and the availability of known in-cylinder technical modifications such as slide valve fuel injectors and injection timing retard that provide significant and cost-effective NOx reductions. It is believed that engines built in 1990 through 1999 are compatible with these lower NOx components. The standards require that engines would need to be modified to achieve a 20 percent reduction in NOx emissions from their existing baseline emission rates.

Reductions in SOx and PM are expected to be met primarily through two approaches. The first would be to operate the engines on a lower sulfur distillate fuel. Category 3 marine engines typically operate on heavy fuel oil with a sulfur content of 2.7 percent. Significant SOx and PM reductions could be achieved using distillate fuels with a sulfur content of 0.1 percent. Fuel costs will be estimated through a separate effort. However, costs due to vessel modifications will be considered here. For instance, if a lower sulfur fuel is used only near U.S. coasts, the vessel must be capable of switching between heavy fuel oil and distillate fuel. In the case of a vessel converting exclusively to distillate fuel, cost savings may be achieved with a greatly simplified fuel treatment system on board the vessel. Alternatively, the vessel could continue to operate on high sulfur fuel if it were equipped with an exhaust gas scrubber to remove SOx from the exhaust.

This report includes descriptions of baseline and likely emission control technologies expected to be used to meet Tier II and Tier III emission standards, the lower sulfur fuel requirement for designated Emission Control Areas, as well as the related costs for application, usage, and maintenance of these technologies.

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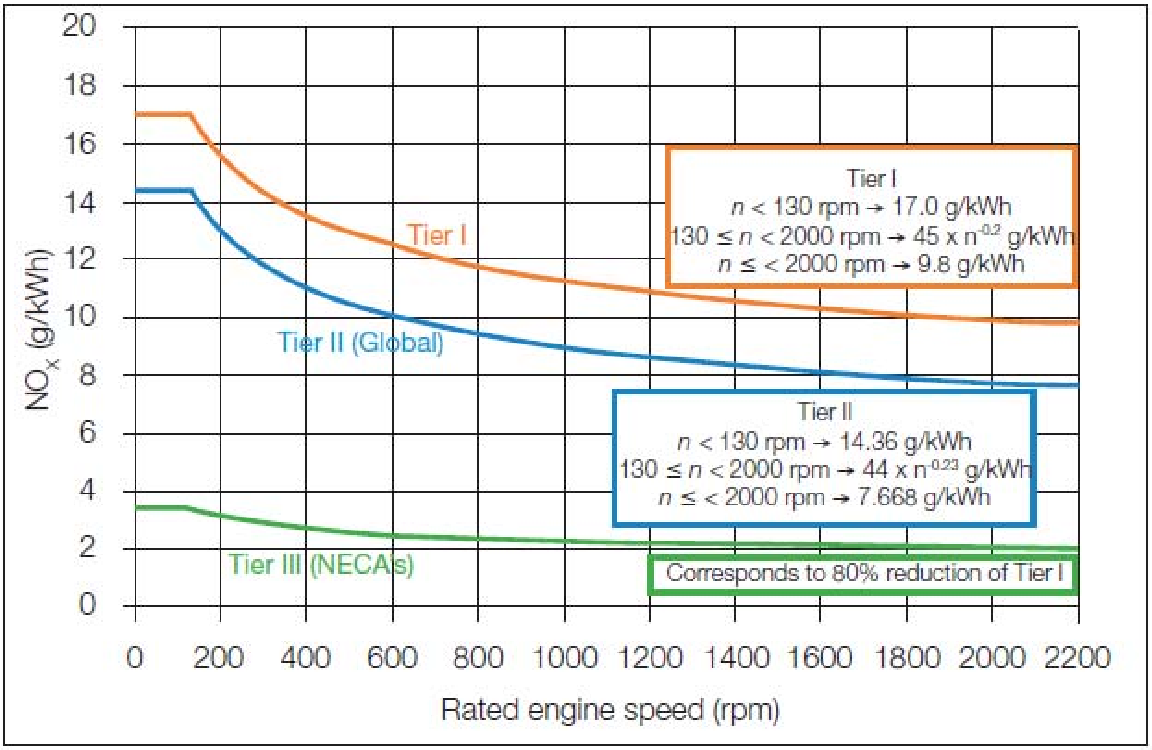
[1] Environmental Protection Agency, "Control of Emissions from New Marine Compression-Ignition Engines at or Above 30 Liters per Cylinder; Proposed Rule," Federal Register / Vol. 72, No. 235 / Friday, December 7, 2007. Available at http://www.epa.gov/fedrgstr/EPA-AIR/2007/December/Day-07/a23556.pdf

[2] Category 3 marine vessel refers to ocean going vessels which have at least one Category 3 marine diesel engine with a displacement of at least 30 liters per cylinder. The standard will apply to all engines on a Category 3 marine vessel including auxiliary engines which are typically Category 2 (5 to 30 liters per cylinder).

[3] Annex VI of MARPOL 73/78: Regulations for the Prevention of Air Pollution from Ships and NOx Technical Code from the IMO (ISBN 92-801-6089-3) (IMO Sales Number IMO-664E)

Figure 1-1. Proposed IMO Standards



Source: MAN Diesel SE[4]

[4] MAN Diesel, "Exhaust Gas Emission Control Today and Tomorrow," August 19, 2008, available at http://www.manbw.com/article_009187.html

2. Technology Description

Category 3 marine diesel engines are currently being built to meet Tier I IMO MARPOL Annex VI emission standards. A brief description of the baseline technologies is given below as well as descriptions of the various technology improvements used to obtain lower emission levels.

2.1. Baseline Technologies

Current engines built to meet MARPOL Tier I emission levels are considered baseline technologies for this analysis. Generally Tier I NOx emission levels are estimated as 11 percent below Tier 0 emission levels.[5] Engine modifications currently being used by manufacturers are listed in Table 2-1. To assess the costs of new technologies needed to reduce emissions below future MARPOL levels, average engine characteristics have been defined. In order to account for different technology costs that are associated with different size and/or types of engines, a number of 'average engines' were developed; these engines with 'typical' characteristics are listed in Table 2-2. Both low-speed and medium-speed Category 3 engines are represented. Estimated costs would need to be adjusted for larger or smaller engines of each type.

Table 2-1. Engine Modifications Currently In-Use to Meet MARPOL Emission Levels[6]

Component or Operation Changed	Change	Parameter Affected	Low-Speed Engines	Medium-Speed Engines
turbocharger	improved efficiency, schemes for variable flow	SFC, intake pressure	yes	yes
Intercooler	improved efficiency	air inlet temperature	yes	yes
air inlet port	redesigned shape	swirl	maybe	yes
cylinder head	redesign shape	swirl, compression ratio	maybe	yes
piston crown	redesigned piston crown shape	swirl, compression ratio	no	yes
injection pressure	increase	atomization	yes	yes
injectors	redesign	sac volume, injection rate shaping	yes	yes
nozzle	smaller holes, more holes, cleaner holes, etc.	spray pattern changes	possibly	yes
injection timing	retard and/or vary with load	peak cylinder temperature	yes	yes
exhaust valve timing	"Miller cycle" timing	peak cylinder temperature	yes	yes

5 Conversation with Michael Samulski of EPA, May 2007.

6 Melvin Ingalls and Steven Fritz, "Assessment of Emission Control Technologies for EPA Category 3 Commercial Marine Diesel Engines," Southwest Research Institute Report, September 2001.

Table 2-2. Average Engine Characteristics Used in this Study

Engine Type	Medium-Speed			Low-Speed		
Engine Power (kW)	4,500	9,500	18,000	8,500	15,000	48,000
Cylinders	9	12	16	6	8	12
Liters/cylinder	35	65	95	380	650	1400
Engine Speed (rpm)	650	550	500	130	110	100
BSFC (g/kWh)		210			195	

2.1.1. Low-Speed Engines

Low-speed engines are usually two-stroke engines with large displacements up to 2000 L/cylinder and are used for propulsion on bulk carriers, container ships, larger tankers, general cargo and roll-on/roll-off ships. They are typically turbo-charged with aftercooling and have four exhaust valves per cylinder. Scavenge air enters the cylinder through a series of intake ports arranged around the bottom of the cylinder. Intake is controlled by the piston as it uncovers or covers the intake ports. Fuel injection is typically mechanical with 3 injectors per cylinder. They typically have 4 to 20 cylinders.

2.1.2. Medium-Speed Engines

Medium-speed engines are usually four-stroke engines with significantly smaller cylinder displacement (30 to 200 L/ cylinder) than low-speed engines. They are typically used as propulsion engines on smaller tankers, general cargo, roll-on/roll-off ships, ferries, cruise ships, and as auxiliary engines on large ships for power generation or refrigeration. They are commonly turbo-charged and aftercooled, have two intake and two exhaust valves per cylinder and are mechanically injected with one injector per cylinder. They typically have 6 to 18 cylinders.

2.1.3. Typical Ship Characteristics

In order to better understand various ship types as they approach U.S. ports, average ship characteristics were determined for each ship type based upon the 2002 Category 3 Marine Vessel Port Inventory.[7] This information is used to determine average time per port call as well as average auxiliary to propulsion power ratios.

[7] ICF International, "Commercial Marine Port Inventory Development – 2002 and 2005 Inventories," September 2007. Available at http://www.regulations.gov/fdmspublic/ContentViewer?objectId=090000648037139b&disposition=attachment&contentType=pdf

Table 2-3. Average Ship Characteristics by Ship Type

Ship Type	Average Propulsion Power (kW)	Service Speed (knots)	Auxiliary Power Ratio[8]	Average Auxiliary Power (kW)	2002 Calls
Auto Carrier	11,155	18.7	0.266	2,967	3,306
Bulk Carrier	8,350	14.5	0.222	1,854	9,600
Container	26,211	21.6	0.220	5,747	14,703
General Cargo	6,709	15.2	0.191	1,281	7,391
Passenger	34,800	20.9	0.278	9,674	3,623
Reefer	10,060	19.5	0.406	4,084	1,447
RoRo	11,687	16.8	0.259	3,027	2,137
Tanker	9,667	14.8	0.211	2,040	13,310
Average	15,244	17.4	0.227	3,533	55,517

Average auxiliary engine load factors and average hotelling time by ship type are given in Table 2-4 for ships calling on U.S. ports in 2002.

Table 2-4. Average Auxiliary Engine Load Factors and Hotelling Times by Ship Type

Ship Type	Auxiliary Load Factors				Hotel (hrs)
	Cruise	Transit	Maneuver	Hotel	
Auto Carrier	13%	30%	67%	24%	45.0
Bulk Carrier	17%	27%	45%	22%	88.0
Container	13%	25%	50%	17%	48.0
General Cargo	17%	27%	45%	22%	88.0
Passenger	80%	80%	80%	64%	11.0
Reefer	15%	30%	45%	30%	60.0
RoRo	20%	34%	67%	34%	45.0
Tanker	13%	27%	45%	67%	38.0
Average	19%	30%	51%	35%	55.5

2.2. Advanced Technologies

Technologies that can be used to meet Tier II and Tier III emission levels are discussed in this section along with those that would be used to retrofit engines built between 1990 and 1999 to meet Tier I emission levels.

2.2.1. Tier I Retrofit Technologies

The October 2008 amendments to MARPOL Annex VI include regulations on ships constructed on or after January 1, 1990 but prior to January 1, 2000 for marine diesel engines with a per cylinder displacement of at least 90 liters and with a power output of over 5,000 kW. Such engines must be retrofit and be certified confirming the engine meets Tier I standards. Most manufacturers will comply with the regulation by providing retrofit kits which contain modified

[8] Ratio of total auxiliary engine power to total propulsion power. These were determined from a survey of 327 ships in January 2005 by the California Air Resources Board.

fuel injectors and possibly modified injection timing. Approximately all Category 3 ships with slow speed diesel engines constructed between 1990 and 1999 have engines with over 90 liters per cylinder while approximately 35 percent of Category 3 ships with medium speed diesel engines constructed between 1990 and 1999 have engines with over 90 liters per cylinder.

Retrofit kits for slow speed diesel engines will include low-NOx slide valves. Slide valves have zero sac volume so fuel dribbling into the engine cylinder after injection is minimized. This leads to lower HC and CO emissions as well as lower PM emissions because any fuel that dribbles into the engine cylinder after combustion will tend not to burn completely. In addition, low-NOx slide valves have optimized spray patterns which minimize NOx formation. Low-NOx slide valves have been shown to reduce NOx from 20 to 25 percent with a 1 to 2 percent fuel consumption penalty.[9]

Retrofit kits for medium speed engines would likely include injectors modified for low NOx performance and injection timing retard. By locating the flame zones closer to metal surfaces (cylinder head, piston) NOx can be reduced in medium speed engines.[10] Cooling of the flame and/or burnt gases by surfaces reduces NOx. Too much cooling, or impingement of unburnt fuel on metal surfaces would increase smoke. By changing the spray cone angle, NOx can also be reduced. It is expected that NOx optimized nozzles could provide a 20 to 25 percent drop in NOx with in a 1 to 2 percent fuel consumption penalty.

2.2.2. Tier II Technologies

Most engine manufacturers can reach Tier II levels with engine modifications. Some of the older mechanically injected engines will be replaced with common rail fuel injection systems.[11] However, it is estimated that approximately 20 percent of low speed engines and 60 percent of medium speed engines may still be mechanically injected. Engine modifications include retarded fuel injection timing, higher compression ratios, lower excess air ratios, lower inlet air temperatures, better fuel distribution, improved nozzle sac design, and use of Miller cycle valving. MAN Diesel estimates a 4 to 6 g/kWh increase in specific oil fuel consumption (SOFC) to meet Tier II regulations.[11]

2.2.2.1 Fuel Injection Timing

By injecting later in the engine cycle, maximum cylinder pressure is reduced, thereby lowering peak cylinder temperatures and thus NOx production. However, lowering maximum cylinder pressure also reduces engine efficiency and increases particulate emissions. In one instance, by retarding the injection by 2º crank angle, cylinder pressures were reduced by about 10 bar and NOx emissions were reduced by about 10 percent; however, fuel consumption was increased by about 1.5 percent.[12] Maximum NOx reductions through this method are about 25 percent, but can be limited by turbocharger speed, because more energy escaping the exhaust will provide more energy to the turbocharger, thereby increasing cylinder pressures.

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[9] Goldsworthy, L., "Design of Ship Engines for Reduced Emissions of Oxides of Nitrogen," in Engineering a Sustainable Future Conference Proceedings. July 2002. Available at http://www.amc.edu.au/system/files/shipNOx.pdf

[10] Paro, D., "Development of the Sustainable Engine," 23rd CIMAC Congress, 2001.

[11] MAN Diesel, "Exhaust Gas Emission Control Today and Tomorrow," August 19, 2008," available at http://www.manbw.com/article_009187.html

[12] Geist et al., "Marine Diesel NOx Reduction Technique- A New Sulzer Diesel Ltd Approach," SAE paper 970321.

Retarding fuel injection timing also increases the exhaust temperature. Exhaust valves need to be kept below 450°C to prevent excessive damage and short operational life. In many cases, exhaust valves are additionally cooled and exhaust valve faces are clad with erosion-resistant materials. Higher grade cylinder liners are used to reduce wear. Pistons are also additionally cooled with oil jets and clad to prevent hot spots and piston damage.

2.2.2.2 Higher Compression Ratio

The effective compression ratio of an engine can be increased by increasing the geometric compression ratio by installing piston rod shims, varying the valve timing or by increasing the scavenge air pressure. Raising compression ratio generally increases NOx while reducing PM and BSFC. When higher compression ratios are used with fuel injection timing retard, the compression pressure increase due to combustion is minimized and thereby NOx emissions are reduced. Varying valve timing or increasing the scavenge air pressure; however, influence the excess air ratio so NOx formation rates are affected as well (see Section 2.2.1.3 below). The maximum achievable NOx reductions of 25 percent from fuel injection timing retard can be achieved without a fuel consumption penalty if the compression ratio is raised. The maximum compression ratio is limited by the structural strength of the engine. Additional strengthening of the rods, crankshaft, piston, head, and cylinder liner are sometimes needed to handle the additional combustion pressures and temperatures.

2.2.2.3 Excess Air Ratio

Oxygen concentration in the fuel/air mixture affects NOx emission formation. Lowering the air excess ratio from 2.2 to 1.9 by adjusting the valve timing and compression ratio at the same time to keep the effective compression ratio constant can reduce NOx emissions by about 15 percent and result in a slight reduction in fuel consumption[12] Lowering the excess air ratio increases the thermal load on the engine, thereby limiting the amount of NOx reduction possible from this method.

2.2.2.4 Inlet Air Temperature

By lowering the scavenge air temperature, NOx emissions can be decreased. In most engines, the scavenge air temperature is limited by the cooling water temperature. However, use of a separate circuit aftercooling system (which utilizes an additional heat exchanger for the aftercooler) can further reduce the air temperature and provide substantial reductions in NOx emissions while providing a reduction in fuel consumption. Some engines already use separate circuit aftercooling, while others install the aftercooler prior to the engine cooling circuit, ensuring it receives cooler water than the after the engine water jacket. Separate circuit aftercooling provides larger benefits than just plumbing the aftercooler first in the engine cooling circuit because lower inlet temperatures can be achieved with separate circuit aftercooling.

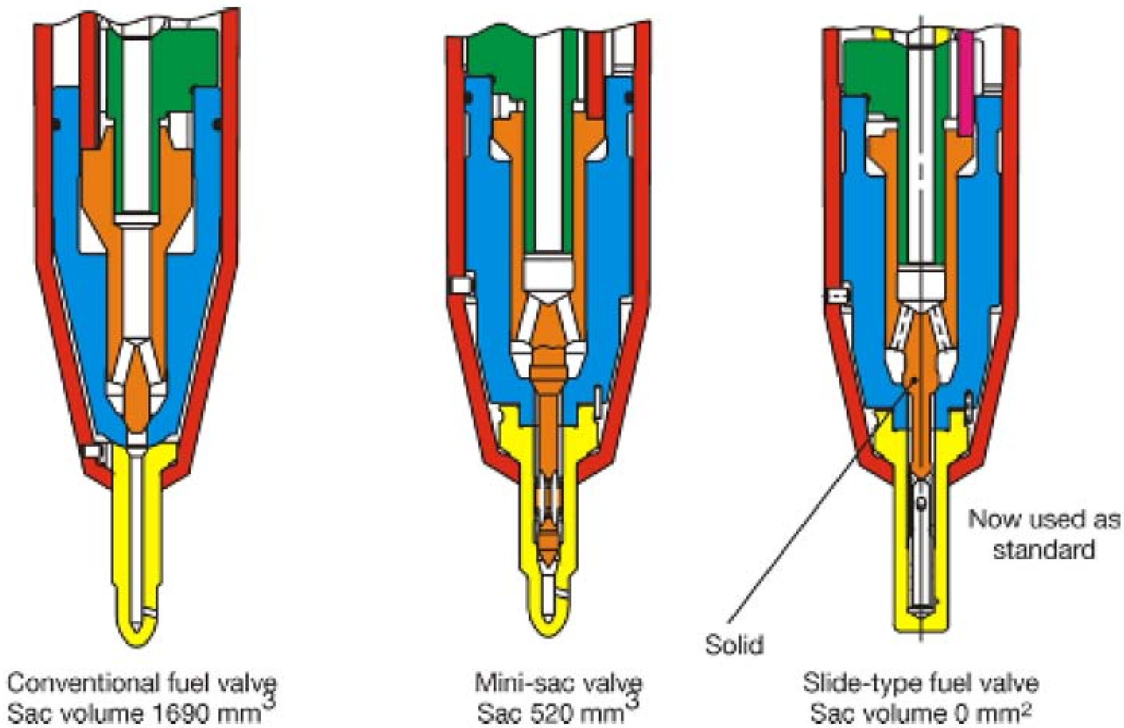
2.2.2.5 Fuel Distribution

Fuel distribution in the cylinder is influenced by intake air swirl, the number of injection nozzles, the fuel spray pattern, droplet size and to a lesser degree, injection pressure. The interaction between the sprays from individual nozzle holes has a significant impact on NOx. There exists an optimum number of nozzle holes for minimum NOx. In addition the angle of the spray cone can also affect NOx. By directing the spray near the piston, there is less air entrainment in the earlier stages of injection leading to lower NOx emissions. This can also enhance turbulence and mixing during the latter stage of combustion which reduces emissions and fuel consumption. NOx reductions of 30 percent have been achieved in some engines, but in most cases there is a strong trade-off between NOx reductions and fuel consumption.[9]

2.2.2.6 Nozzle Sac Design

By reducing nozzle sac volume, particulate and hydrocarbon emissions are reduced. The nozzle sac is the small volume at the end of the nozzle that can contain trapped fuel after the injector valve closes. This fuel tends to dribble into the cylinder later in the cycle and tends to result in both hydrocarbon and particulate emissions. By eliminating the sac volume, hydrocarbon emissions can be reduced up to 75 percent at full load.[13] Most low speed engines already use slide valve nozzles to meet Tier I emission levels. Diagrams of nozzle sacs are shown in Figure 2-1.

Figure 2-1. Cross-Sectional diagrams of Different Nozzle Sac Designs



Source: Man B&W[14]

2.2.2.7 Miller Cycle Valving

By using high pressure turbocharging and closing the intake valve before the piston reaches bottom dead center (BDC) during the intake stroke, the entrapped air charge will be expanded and reach the pressure of a normal turbocharged engine at BDC, but at a significantly cooler temperature due to the expansion. This leads to the bulk cylinder temperature being lower

[13] Ole Grøne and Kjeld Aabo, "How to meet local and international marine emission legislation," presented to the Institute of Marine Engineers in Rotterdam, September 2001

[14] Kjeld Aabo, "Marine Transport Fuels and Emissions," presented at the Third Nordic-Japan Environmental Conference in Nagano, Japan, November 2002.

during the entire combustion process, which directly reduces NOx emissions. Miller supercharging can reduce NOx by 20% without increasing fuel consumption.[9]

2.2.2.8 Common Rail Injection/Electronic Fuel Injection

The common rail refers to a rail or tube running the length of the engine below the level of the cylinder cover. Heated fuel is supplied to the common rail injection system at high pressure, ready for injection. Injection occurs under constant fuel pressure via electronic/hydraulic high-pressure pumps running on multi-lobe cams.

One manufacturer's heavy fuel common rail system is constructed from a series of inter-connected accumulators. Each common rail injection pump supplies two accumulators. The design can be retrofitted to existing engines by simply removing the current injection pumps and replacing them with a common rail delivery pump and an accumulator. Each accumulator is connected directly to two injectors and each line contains a flow fuse for safety. A flow control valve regulates the rail pressure on each of the rail pumps. The regulation signal to the flow control valve comes from the electronic control system. The fuel oil injection timing and duration are electronically controlled as well. High pressure engine lubricating oil is used to open the fuel injection valve.

NOx reductions from common rail systems are mostly due to the ability to control the amount and rate of fuel injection at low loads as opposed to mechanical injection systems. Mechanical systems generally do not have the flexibility to provide the right amount of fuel for all load settings. Because the right amount of fuel can be injected at all loads, fuel consumption is reduced. Outside of its utility for NOx reductions, this technology also reduces visible smoke from unburned excess fuel from cruise ships because it limits over-fueling during maneuvering.

This technology is currently being demonstrated on a low-speed diesel engine constructed by Sulzer, called the Sulzer R-T flex engine. It has been estimated that use of the Sulzer R-T flex engine, and its common-rail fuel injection system, can provide 20% lower NOx emissions over current Tier I standards. Table 2-5 presents key features and benefits of the Sulzer design.[15] A diagram of a Wärtsilä common rail system is shown in Figure 2-2.[16]

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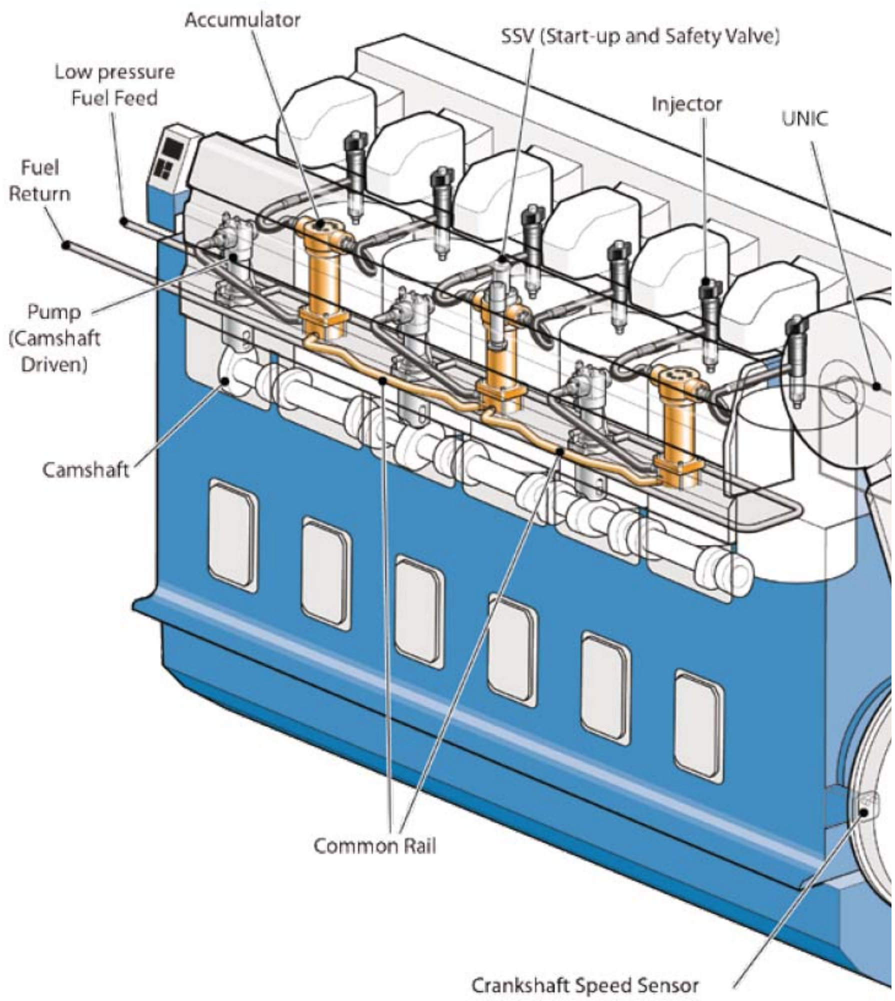
[15] Stefan Fankhauser, "World's first common-rail low-speed engine goes to sea," Marine News, No. 3-2001, pg 12-15

[16] Wärtsilä Corporation, "Wärtsilä Common Rail – A Super Efficient Fuel Injection System," February 2007, available at http://www.wartsila.com/Wartsila/global/docs/en/about_us/twentyfour7/2_2007/common_rail_injection_system_infographics.pdf

Table 2-5. Key Attributes and Benefits to the Sulzer RT-flex Common Rail System

Key Features	System Benefits
o Precise volumetric control of fuel injection, with integrated flow-out security o Variable injection rate shaping and free selection of injection pressure o Ideally suited for heavy fuel oil o Proven, high-efficiency supply pumps o Lower levels of vibration and internal forces and moments o Steady operation at very low running speeds with precise speed regulation	o Reduced maintenance requirements o Full electronic common-rail control with integrated monitoring functions o Better fuel economy (currently due mainly to part-load operation) o Easier compliance with the NOx emission limit in Annex VI of the MARPOL 73/78 convention o Lower steady running speeds, down to 12 rpm o No visible smoke at any operating speed

Figure 2-2. Wärtsilä Common Rail Fuel Injection System



Source: Wärtsilä Corporation[15]

A second manufacturer has installed an electronically controlled cam-less engine using an in-house developed electronic-hydraulic platform on a 37,500 DWT deep sea chemical carrier.[17] The system allows for electronically controlled fuel injection and exhaust valve actuation which permit individual and continuous adjustment of the timing for each cylinder. Parts that are removed from the mechanical system include the chain drive for camshaft, camshaft with fuel cams, exhaust cams and indicator cams, fuel pump actuating gear, including roller guides and reversing mechanism, conventional fuel injection pumps, exhaust valve actuating gear and roller guides, engine driven starting air distributor, electronic governor with actuator, regulating shaft, mechanical engine driven cylinder lubricators, and engine side control console. The items added to the engine include a hydraulic power supply, hydraulic cylinder unit with electronic fuel injection and electronic exhaust valve activation, electronic alpha cylinder lubricator, electronically controlled starting valve, local control panel, control system with governor, and condition monitoring system. Two electronic control units are used to control the system with one being a backup for the first. The manufacturer claims that the electronic version of the engine was very easy to adjust to the prescribed setting values and was able to keep the very satisfactory setting values without further adjustments since the vessel's sea trials in November of 2000.

A third manufacturer has further developed mechanically-actuated electronically-controlled unit injectors and hydraulically actuated electronically-controlled unit injectors to provide the flexible fuel injection characteristics needed to optimize engine performance and emissions.[18] The manufacturer states that the design approach in both injector concepts is to utilize a Direct Operated Check (DOC) to precisely control the pressure, timing and delivery of fuel. The DOC is applicable to electronic unit injector or unit pump configurations with either mechanical or hydraulic actuation of the pressurizing units. The manufacturer has claimed the technology eliminates spray distortion and minimizes parasitic losses which may be seen in common rail fuel systems. The manufacturer includes discussion on closed loop NOx control in the reference paper. They state that ultra fast NOx sensors are a key part to closed-loop control of NOx emissions. The sensors provide the benefits of minimized engine to engine variations, minimized cylinder to cylinder variations and improved transient response with reduced emission and reduced operational costs.

2.2.3. Tier III Technologies

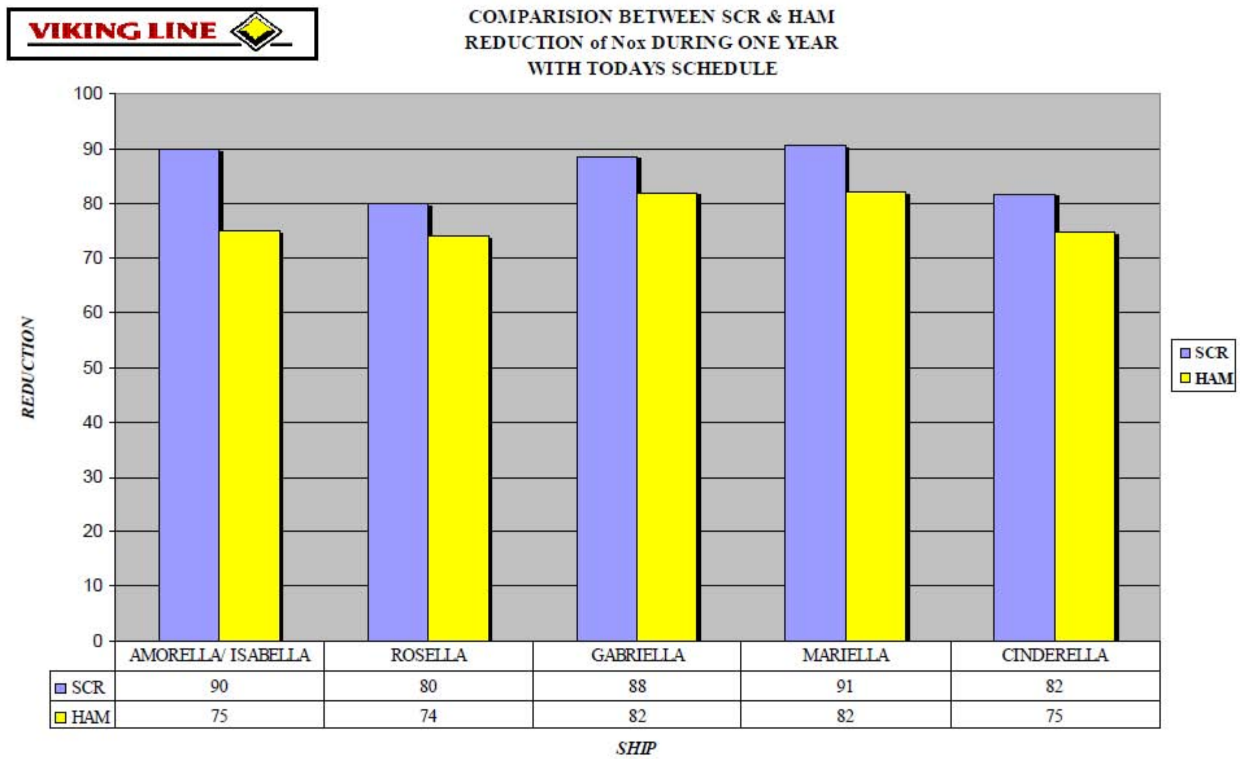
Tier III emission levels will require large reductions in NOx and SOx emissions. Most engine manufacturers believe they will use SCR in combination with lower sulfur marine diesel oils (MDO) or marine gas oils (MGO) to meet Tier III standards. However, other NOx reduction techniques include introduction of water into the combustion chamber either through fumigation, fuel emulsions or direct water injection and exhaust gas recirculation. . In fact, Viking Line produced simillar NOx reductions to SCR using a HAM system as shown in Figure 2-3.[19] While SCR outperformed the HAM system on all five ships, the reductions were close. With EGR and a HAM system, NOx reductions approaching those for SCR could be achieved.

[17] Sorensen,Per andPedersen, Peter, "The Intelligent Engine Design Status and Service Experience," International Council on Combustion Engines, CIMAC Congress 2001

[18] Moncelle, M.E., "Fuel Injection System & Control Integration," International Council on Combustion Engines, CIMAC Congress 2001.

[19] Presentation of Ulf Hagstrom, Marine Superintendent, Technical sector, Viking Line Apb, "Humid Air Motor (HAM) and Selective Catalytic Reduction (SCR) Viking Line," at Swedish Maritime Administration Symposium/Workshop on Air Pollution from Ships (May 24-26, 2005)

Figure 2-3. Comparison between SCR and HAM



Other techniques to reduce emissions will include compound or two-stage turbocharging as well as electronic valving to enhance performance and emission reductions. To meet low SOx requirements, shipping fleets will either use sea water scrubbers or fuel switching to lower sulfur fuels or run full time on lower sulfur fuels.

2.2.3.1 Engine Modifications

Engine modifications to meet Tier III emission levels will most likely include a higher percentage of common rail fuel injection systems coupled with the use of two-stage turbocharging and electronic valving. Engine manufacturers estimate that practically all low speed engines and 80 percent of medium speed engines will use common rail fuel injection. Two stage turbocharging will probably be installed on at least 70 percent of all engines produced to meet Tier III emission levels. Electronically (hydraulically) actuated intake and exhaust valves for medium speed engines and electronically actuated exhaust valves for low speed engines are necessary to accommodate two-stage turbocharging.

Two-stage turbocharging is set up in various fashions. The most popular set up is to use one smaller and one larger turbo. The larger turbo's compressor stage blows into the smaller one's compressor stage. The exhaust is set up the other way round: it first enters the turbine of the smaller turbo, and then the turbine of the larger turbo. Two-stage turbocharging systems were shown to improve considerably the performance of four-stroke engines, showing potentials for reducing NOX emissions by up to 50 percent at certain load ranges together with some savings in fuel consumption. Good part-load performance was ensured by using a variable inlet valve closure (VIC) system which enables the Miller effect to be varied according to engine mean effective pressure (BMEP).[20] Electronically actuated valves allow variable intake and exhaust valve opening and closing which enhances the Miller effect.

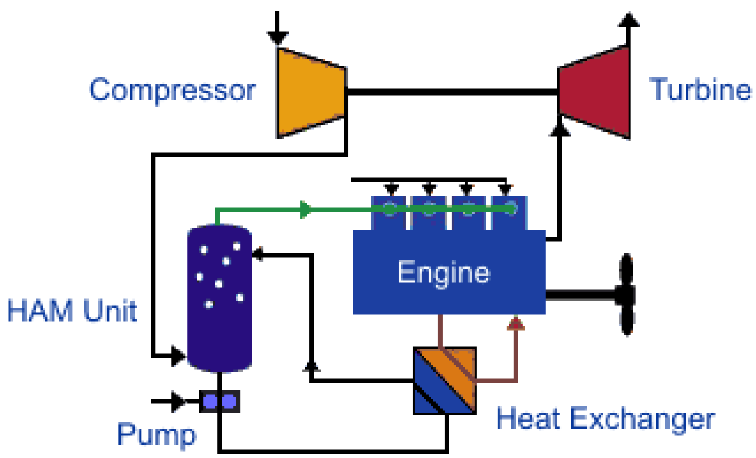
2.2.3.2 Fumigation

There are currently three types of fumigation systems, namely the Humid Air Motor (HAM), the Scavenged Air Moisturizing (SAM) system and the Wetpac H.

The HAM process was developed by Munters Europe AB, and has undergone trials for 4000 hours on the MS Mariella in the Viking Line. The HAM system uses heated charge air enriched with evaporated seawater to reduce NOx emissions during the combustion process. The HAM system is used to replace the conventional engine air intercooler. Since it uses engine heat to heat the seawater, additional boiler capacity may be needed for other ship needs.

The central part of the HAM system is a special humidification unit, which is effectively a heat exchanger. This must be mounted very near the engine. Other equipment include a circulation pump and filter, a heat exchanger (to heat the incoming water), a "bleed-off" system (to control the contents of salt and minerals in the water) and a water tank as shown in Figure 2-3.

Figure 2-4. HAM System



Source: Viking Line[19]

Water, which has already been heated by the engine cooling system, is additionally heated and vaporized using hot air from the turbocharger. This humidified charge air is directed into the combustion chamber after filtration for debris. The system has been reported to reduce NOx by 70-80% with water to fuel ratios of 2.8 at normal operating speeds and loads.[21] While MAN B&W has tested HAM units on smaller engines typically on ferries, no tests to date have been done on engines the size used on container or bulk carrier vessels.

In contrast to SCR, no warm-up time is necessary with HAM and NOx reduction commences more or less once the motor is engaged. As a precaution to minimize possible corrosion in the

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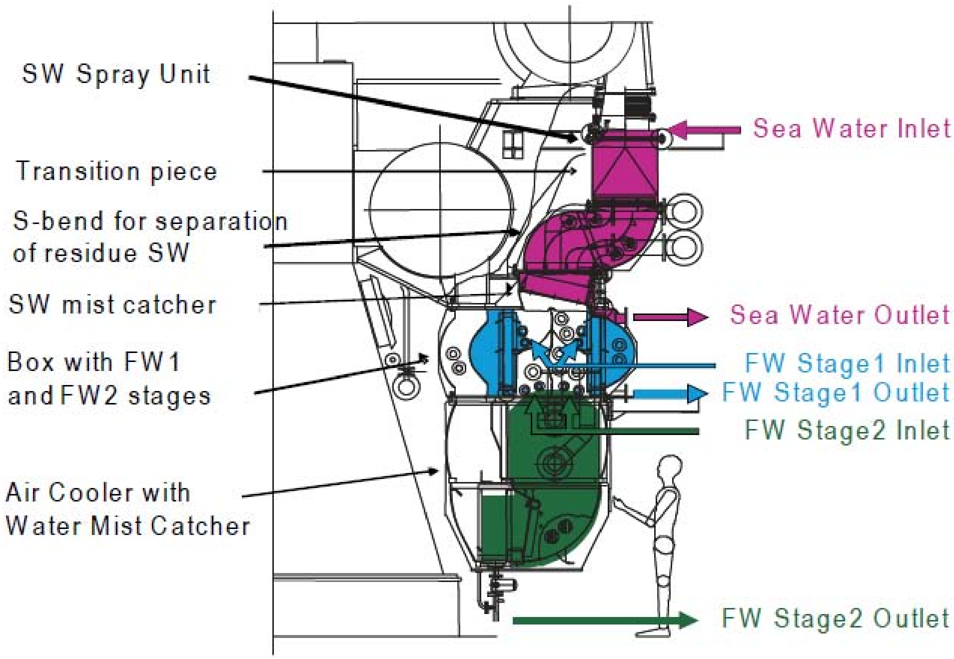
[20] Wartsila Corporation, "Joint diesel research project completed," Trade & Technical Press release, 6 September 2007 available at http://www.wartsila.com/ch,en,press,0,tradepressrelease,3D5201D4-5D37-4E26-B7E8-D4E6F592CE6A,5B771063-161A-4942-810E-5329B81B3565,,.htm

[21] Peter Mullins, "The H.A.M. System Approach to Reducing NOx," Diesel & Gas Turbine Worldwide, November 2000.

humidification unit, it is advised that the water flow is turned off around 15 minutes before engine shut down to dry out the exhaust tower. Although *MS Mariella* operates using a lower sulfur heavy fuel oil (IF 220), an additional claimed advantage over SCR is that HAM is suitable for residual oils with higher sulfur contents of up to 4.5 percent.[22]

The SAM system is being developed by MAN B&W and has been tested on the *M/V Mignon* of the Wallenius-Wilhelmsen Lines. The SAM installed on a B&W 8S60MC engine on the *M/V Mignon* has a sea water injection stage, where a surplus of sea water is injected for saturation and cooling of the hot air from the compressor. The sea water (SW) stage provides nearly 100% humidification of the scavenge air and supplies all of the water for humidification.[11] The SAM system is shown in Figure 2-4. The SAM components in the compressor air cooler arrangement (i.e. SW spray, transition piece, S-bend and inlet box for the fresh water stages [FW1 and FW2]) are manufactured in austenitic stainless 254SMO because of its excellent resistance against corrosion from salt water.

Figure 2-5. SAM System

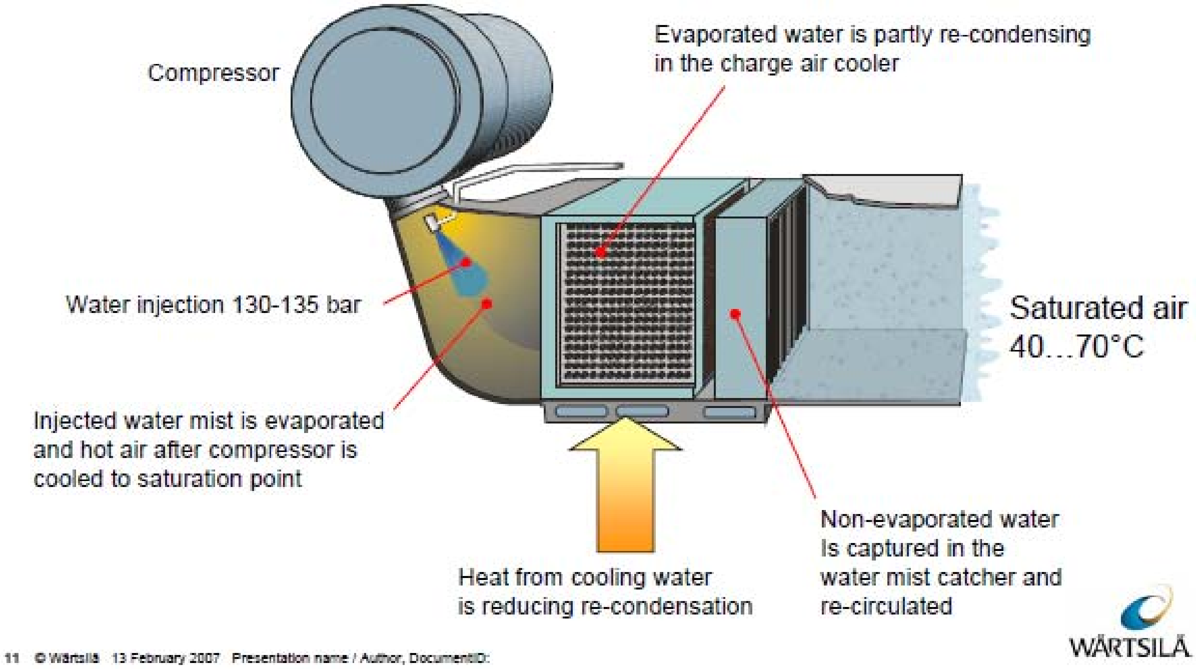


Source: MAN B&W[11]

The Wetpac H is developed by Wärtsilä. The principle of Wetpac H technology is to introduce pressurized water into the combustion process to reduce NOx formation. The pressurized water is added to the intake air after the turbocharger compressor. Due to the high temperature of the compressed air, the water evaporates immediately and enters the cylinders as steam, thus lowering the combustion temperatures and the formation of NOx. Wetpac H technology has so far been developed for the Wärtsilä 20, 32 and 46 engine types, and the first pilot installation was commissioned in 2003. The anticipated NOx reduction is up to 50%, and the water consumption is expected to be about two times the fuel oil consumption. The Wetpac H system is shown in Figure 2-5.

[22] Entec UK Ltd, "Service Contract on Ship Emissions: Assignment, Abatement and Market Based Instruments – Task 2b – NOx Abatement," August 2005 available at http://ec.europa.eu/environment/air/pdf/task2_nox.pdf

Figure 2-6. Wetpac H System



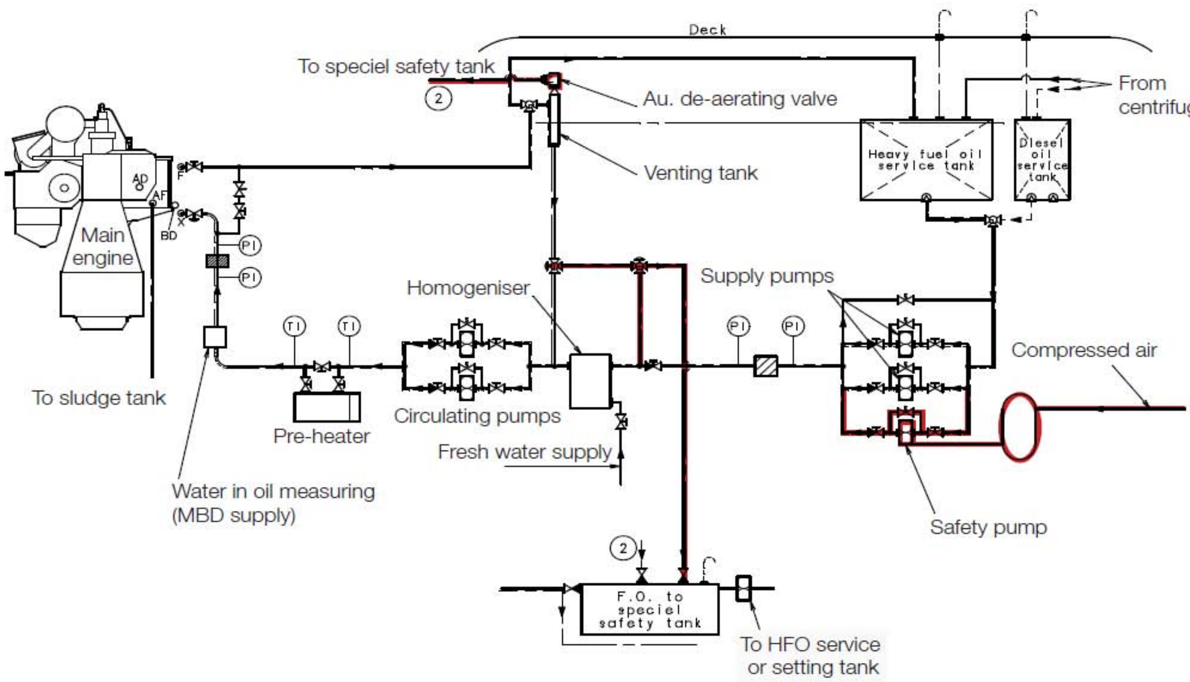
Source: Wärtsilä Corporation[23]

2.2.3.3 Fuel Emulsification

Another method of introducing water into the combustion chamber to reduce NOx production is through water-in-fuel emulsions. MAN B&W has been testing water-in-fuel emulsions since the early 1980s. Formation of the emulsion is achieved within the standard fuel module, which has to be slightly modified. Given that a fuel injector delivers a fixed volume of fuel for a particular power output, the addition of water increases the volume that must be injected. This fact requires that the injector assembly – specifically the atomizer design, must be adapted to the increased injection volume. Fuel emulsification can be used on either mechanical or electronic injection system. A schematic of a pressurized water emulsion system is shown in Figure 2-6.

[23] German Weisser, "Emission Reduction Solutions for Marine Vessels – Wärtsilä Perspective," presented at the Clean Ships – Advanced Technology for Clean Air Conference, February 2007. Available at http://www.cleanshipsconference.com/pdfs/Weisser.pdf

Figure 2-7. Pressurized Fuel Emulsification System



Source: MAN B&W[11]

Water emulsion systems require modification to the fuel pump, camshaft and control system to handle additional water for full load operation. A pressurized system is also needed to avoid cavitation and boiling off in the low pressure part of the fuel system. In addition, a water dosage system and homogenizer is needed. Water's higher viscosity requires the mixture be heated further by about 20°C to properly flow through the injection system. In addition the fuel pressure needs to be raised to keep the water from boiling.

MAN B&W reports no effect on specific fuel consumption. They estimate that with 10% water/fuel ratio, a NOx reduction of 10% can be achieved but the maximum reduction is about 50%.[11] However, in practice NOx reduction is limited by the maximum delivery capacity of the fuel injection pumps. At low ratings or at low load, higher NOx reductions can be achieved. In addition, water emulsification in combination with an electronically controlled engine offers the following additional flexibility advantages:

- Optimal injection rate shaping can be achieved both without and with any water content.
- ''Free rate shaping'' allows the use of large water amounts even at low engine load as pre-injection can be used to compensate for ignition delay.

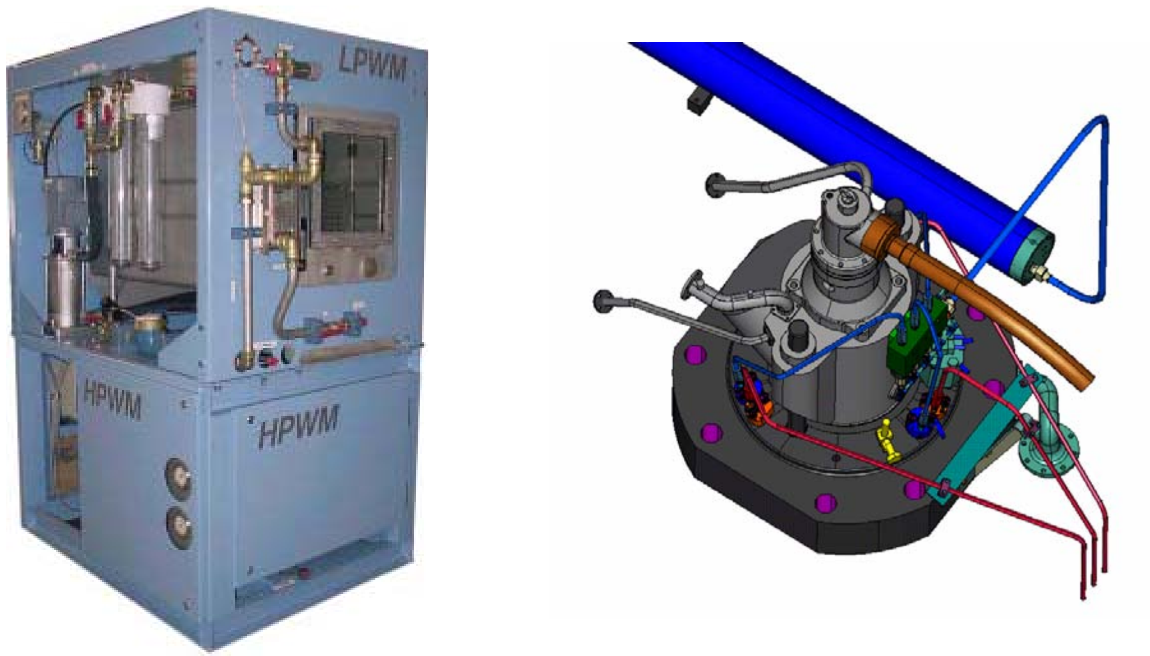
Water-in-fuel emulsification is currently being tested on an 11K90MC engine installed on an APL container vessel. The test is expected to be finalized at the beginning of 2009.[11]

2.2.3.4 Direct Water Injection

Direct Water Injection (DWI) is another method to reduce cycle temperatures and therefore lower NOx emissions. This method has been under development for Sulzer low-speed engines since 1993. Unlike other water techniques, DWI enables water to be injected at the right time and place to obtain the greatest reductions in NOx emissions. The water is injected into the cylinder using a fully independent, second common rail injection system under electronic control. Also in comparison to emulsification, it allows water to be injected into the engine without derating the engine and allows the fuel and water to be injected at different times. Injection can occur either during the compression stroke or with fuel injection so that injection timing can be optimized to both reduce NOx and other emissions without affecting engine reliability. Water injection can be turned off or on without affecting fuel injection behavior. NOx emissions can be reduced 50% using a 0.7 water/fuel ratio.[24] Water is fed to the cylinder head at high pressure (210-400 bar depending on the engine type). High water pressure is generated in a high-pressure water pump module. A low-pressure pump is also necessary to ensure a sufficiently stable water flow to the high-pressure pump. Water entering the low pressure pump needs to be filtered to remove all solid particles. The pumps and filters are built into a module to enable easy installation as shown in Figure 2-7. NOx reduction is most efficient from 40% load and higher of nominal engine output.

DWI requires that fresh water be generated onboard the ship and stored. Currently, a 20 to 50 percent water addition is anticipated, meaning substantial quantities of water must be generated and stored. Fresh water generators can be heated using engine cooling water or using steam from an exhaust gas economizer. In addition, there must be sufficient tank capacity for the water with the necessary handling system.

Figure 2-8. DWI Unit for Pressurizing Water and injectors



Source: Wärtsilä Corporation[25],[23]

[24] H. Schmid and G. Weisser, "Marine Technologies for Reduced Emissions," Wärtsilä Corporation, April 2005. Available at http://www.wartsila.com/Wartsila/global/docs/en/ship_power/media_publications/technical_papers/sulzer/marine_technologies_for_reduced_emissions.pdf

[25] Wärtsilä, "The EnviroEngine Concept," 2004.

DWI is one of the technologies currently being employed by Wärtsilä, which has provided extensive information on the method, as presented in Table 2-6.

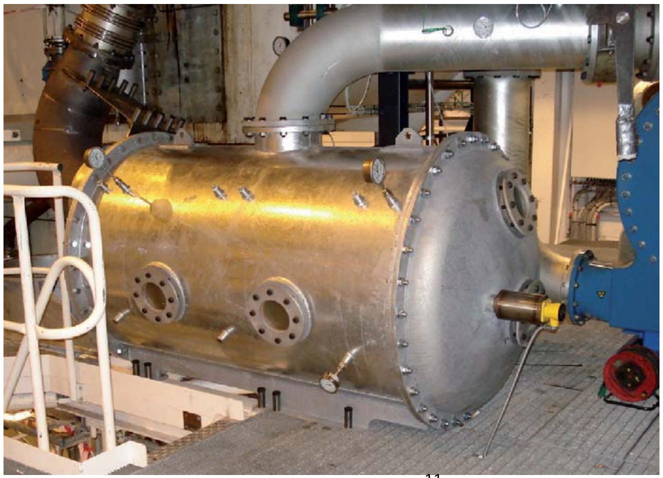
Table 2-6. Benefits and Limitations of Wärtsilä's DWI Technology

Key Benefits	
o NOx emissions are reduced by 50-60% o NOx emissions when running MDO are typically 4-6 g/kWh o NOx emissions when running Residual Oil are typically 5-7 g/kWh o The engine can also be operated without water injection, if necessary o The engine can be transferred to "non-water" operational mode at any load	o In alarm situations, transfer to "non-water" mode is automatic and instant o Space requirements for the equipment are minimal and therefore the system can be installed in all installations o Investment and operational costs are low o Ratio of injected water to injected fuel typically 0.4 to 0.7 o Can be installed while the ship is in operation
System Limitations	
o Cannot be used at its maximum at low loads o Increases fuel consumption o Clean water supply needed	

2.2.3.5 Exhaust Gas Recirculation

MAN Diesel originally tested a simplified exhaust gas recirculation (EGR) system which consisted of a loop from the exhaust gas receiver that went past the last charge air cooler, but connected just before the last water mist catcher on a low speed engine. This was thought to prevent fouling of sensitive engine parts due to high particulate and sulfur oxide levels in the exhaust from burning residual oil. It was originally thought that cleaning the exhaust was necessary to prevent fouling of the air cooler and receiver components. The system had two water injection stages with a simple water separator unit after both. The tests showed a substantial NOx reduction but confirmed that the exhaust gas could not be cleaned sufficiently before entering the air cooler and scavenge air system. More recently, MAN diesel tested EGR with a scrubber and water treatment, obtaining a 70 percent reduction in NOx emissions with a relatively small increase in brake specific fuel consumption (BSFC).[11] MAN diesel used an EcoSilencer® to clean the exhaust gas before reintroducing it into the air cooler and scavenge air. The scrubber removed 90 percent of the PM emissions and 70 percent of the SOx with no water carry over. The EGR scrubber is shown in Figure 2-8.

Figure 2-9. MAN Diesel EGR Scrubber



Source: MAN B&W[11]

2.2.3.6 Selective Catalytic Reduction

The Selective Catalytic Reduction (SCR) process involves injecting a reagent, such as ammonia or urea, into an exhaust flow, upstream of a reactor, to reduce NOx compounds into nitrogen and water. The system effectiveness is strongly dependent on the type of catalyst and the reactor temperature which generally needs to be from 210ºC to 500ºC.[26] For 4-stroke engines with relatively high exhaust temperatures, the reactor unit can be placed downstream from the exhaust manifold as shown in Figure 2-9. Main system components are: an SCR reactor, aqueous urea injection/dosing, and monitoring/control systems. The SCR system does require storage of urea solution on-board in a separate tank.

In order to control ammonia slip (urea that is not used in the SCR unit, escaping to the exhaust) and reach optimal operation of the SCR unit, temperatures, pressures, and other parameters need to be carefully monitored and controlled. In addition, the urea injected into the exhaust stream before the SCR reactor, needs to be well mixed with the exhaust gases before entering the reactor for optimal performance.

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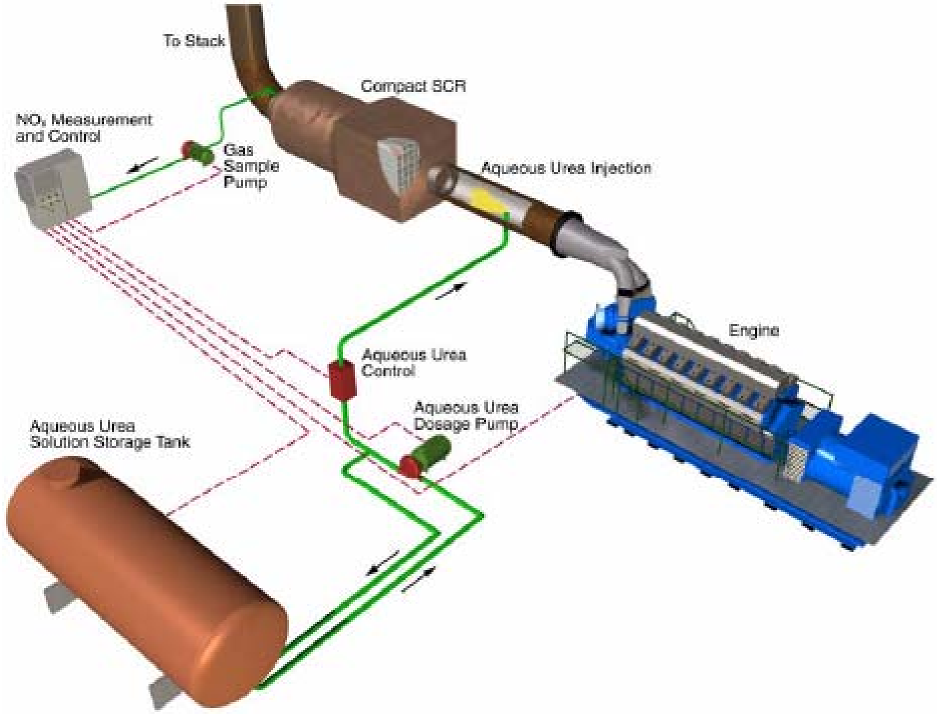
[26] The minimum temperature of 210°C requires 1000 ppm sulfur fuel. The minimum rises to approximately 300°C when 2.5 percent sulfur residual oil is used. While the SCR reactor can handle temperatures of 500°C, engine manufacturers tend to limit exhaust temperatures to 450°C to protect valves from fouling due to vanadium and sodium present in residual oil.

Figure 2-10. Example of Urea SCR System for a 4-stroke engine with the reactor placed downstream of turbocharger

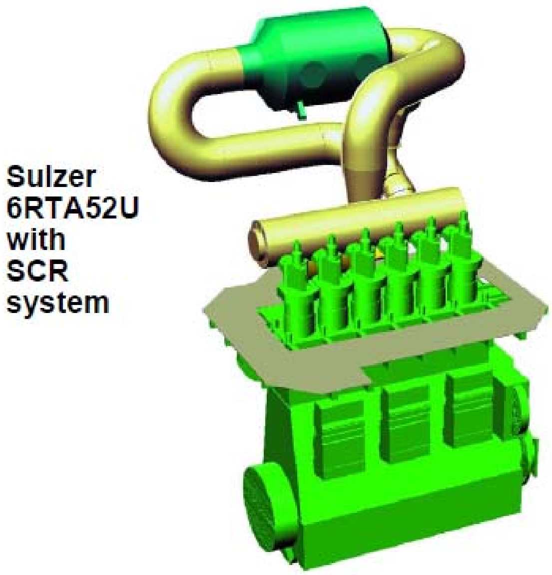


Source: Wärtsilä Corporation[27]

Low-speed and large medium-speed engines operate at relatively low exhaust temperatures such that the SCR reactors need to be located between the turbocharger inlet and the engine's exhaust manifold in order to get enough heat (see figure below).

[27] http://www.wartsila.com/Wartsila/global/docs/en/service/Leaflets/enviro/COMPACT_SCR.pdf

Figure 2-11. Urea SCR system with Reactor Installation before Turbocharger



Source: Wärtsilä Corporation[23]

The urea SCR systems have successfully been used for large stationary source applications where loads are fairly constant. In the marine sector, a majority of the installations of SCR technology have taken place on smaller four-stroke engines as opposed to the larger two-stroke main engines. There are more than 300 marine SCR systems currently in operation developed by Argillon, Wärtsilä, Munters, and other companies. In certain marine engine applications, this technology can be used in conjunction with a diesel oxidation catalyst to reduce PM emissions.

There are reports that a properly designed Urea SCR system can reduce NOx emission by more than 98% but this is most likely with significantly lower sulfur fuel. Clean Diesel Technologies is one company that markets diesel exhaust aftertreatment technologies for various applications including marine and claims that typical NOx conversion efficiency is between 70 to 90 percent in reactors that maintain temperatures above 320°C[28]. Argillon consistently reports that their best designs can maintain 95 percent efficiency under most conditions.[29] Most companies suggest that for analysis purposes 90 to 95 percent NOx reduction efficiency can be assumed for properly designed systems.

In addition to operating temperature sensitivity to high sulfur fuels, high sulfur fuels can also create large amounts of SOx which keep urea SCR reactors from operating effectively. Sulfur oxides can react with oxygen in the exhaust and form sulfuric acid, which can cause corrosion and reduce SCR system life. Also high levels of SOx can interfere with the NOx reduction reaction decreasing the SCR system effectiveness. In addition if the exhaust temperature is too low, ammonia salts will form on the SCR unit which can essentially plug the reactor. This is more a problem with low speed engines than medium speed engines. In those cases, the SCR unit will be shut off to prevent ammonia salt formation.

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[28] Clean Diesel Technologies corporate website http://www.cdti.com/content/technology/overview.htm

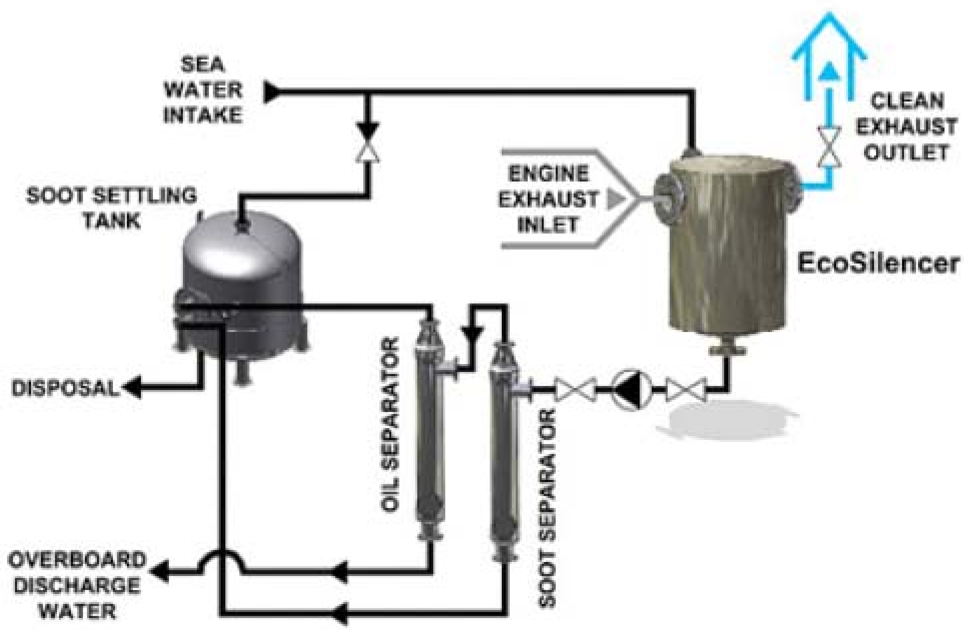
[29] Argillon Website, http://www.argillon.com/business-segments/systems/industrial-applications/overview.html

2.2.3.7 Sea Water Scrubbers

Seawater scrubbing technology is designed to reduce SOx and PM emissions from large marine and stationary engines situated near a shoreline. The technology uses wet Flue Gas Desulphurization, which is the mixing of hot exhaust flue gases with seawater. Seawater is alkaline by nature and rich in calcium sulfates which react well with acidic gases like SO_2. The reaction forms products which are soluble in water and can be discharged overboard in open sea operation. For areas where acidic water discharge is a concern, for example port operation, the water from a scrubber is diluted with additional seawater before discharge.

Figure 2-11 provides a simplified schematic of one seawater scrubber design (by MES). These systems are very effective at removing SO2 and the direct sulfate component of the exhaust PM. Carbonaceous PM in the engine exhaust is removed through impaction; however, much of the carbonaceous PM can be trapped in bubbles and may pass through the scrubber, so PM treatment efficiency in the seawater scrubber is highly dependent on the design. The captured PM can be removed from the stream exiting the scrubber by filtering and is kept in a settling or sludge tank for later disposal.

Figure 2-12. Seawater Scrubbing System with EcoSilencer® for a "Super Yacht" design for engines up to 3.5MW



Source: Marine Exhaust Solutions, Inc.[30]

While the scrubber design parameters such as reactor volume will greatly impact its effectiveness, the technology efficiency also depends on the SOx concentration in engine exhaust, as well as factors such as seawater temperature or salinity. Marine Exhaust

[30] Hamid Hefazi and Hamid R. Rahai, Center for Energy and Environmental Research and Services, California State University, Long Beach, "Emissions Control Technologies for Ocean Going Vessels," Final Report Submitted to State of California ARB, June 2008

Solutions[31], a Canadian company, for example, claims that for engines burning up to 4.5 percent sulfur fuel, their EcoSilencer® system will reduce SO_2 emissions by up to 90 percent (higher with lower sulfur fuel). It will also eliminate up to 90 percent of visible PM (up to 50 percent by mass), as well as reduce approximately 3 to 5 percent NOx. The company claims that the system can be used in wide range of engines from 0.1 to 100MW.

Various scrubber designs are marketed by different companies. There are industry claims that properly designed systems are capable of nearly complete removal of sulfur compounds from engine exhaust, as well as up to 80 percent PM removal.[32]

The seawater scrubbing systems do result in a fuel economy penalty in terms of pumping power since large amounts of wash water needs to be circulated through the system. Industry estimates of the penalty vary but generally fall within 1 to 3% range depending on operating and fuel quality conditions.

2.3. Fuel Switching

Switching from a heavy fuel oil (HFO) with an average sulfur content of 2.7 percent to a distillate fuel, such as marine distillate oil (MDO) or marine gas oil (MGO) with a sulfur content of 0.1 percent, either permanently or temporarily, can provide significant SOx and PM reductions. However in some cases, vessel modifications may be necessary to achieve this, as it means either migrating from the unifuel model or use of the more expensive distilled fuel all the time. The following section discusses the systems needed to deliver these fuels. The next section discusses technical obstacles of fuel switching. The final section discusses modifications needed for fuel switching.

2.3.1. Vessel fuel systems

Some current marine vessels are powered by low-speed, 2-stroke, marine diesel engines, operating in a unifuel mode on heavy fuel oil.[33] Unifuel refers to operating essentially all engines on the same fuel type – typically HFO[34]. Note that, in this system, both main and auxiliaries are powered by HFO but relatively small amounts of lighter distillate oil are also carried for long term shutdown and emergency use.[35] Prior to long term shutdown, the engines are operated on distillate fuel to purge the HFO from the fuel system.

HFO contains contaminants and other residual fuel components that must be treated, purified, and/or removed and heated to obtain appropriate viscosity onboard before injection into a compression ignition engine. Although, generally heavier fuels require more complex fuel treatment systems, all systems prevent heavy fuel oils from solidifying in the fuel system,

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[31] Marine Exhaust Solutions, Inc. Corporate website http://www.marineexhaustsolutions.com/

[32] Krystallon, "Sea Water Scrubbing, Facts and Fantasy," Presentation at Clean Ships Conference, Sand Diego, CA, February 9, 2007.

[33] Global Trade and Fuels Assessment "Future Trends and Effects of Requiring Clean Fuels in the Marine Sector," Prepared for EPA by RTI International, EPA420-R-08-021, November 2008, available at: http://www.epa.gov/oms/regs/nonroad/marine/ci/420r08021.pdf. This report, in turn, is based largely on the Fuel Switching presentations to the California ARB, 7/27/08, available at http://www.arb.ca.gov/ports/marinevess/presentations.htm. First order references are provided where appropriate.

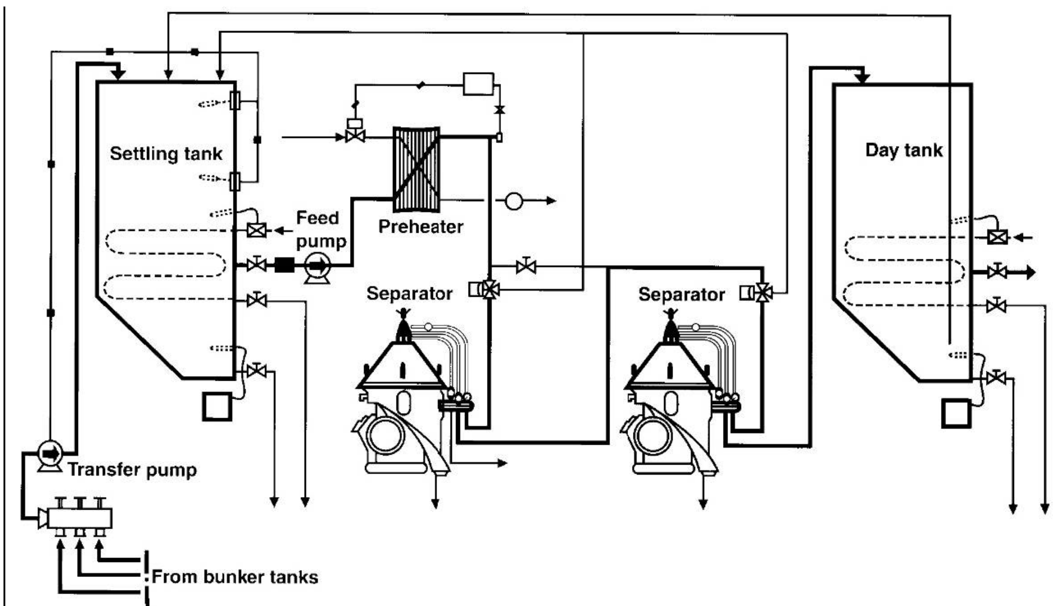
[34] Also referred to as residual oil (RO). Intermediate fuel oil (IFO) is used commonly.

[35] Keith Michel, Herbert Engineering Corp., "California Maritime Technical California Maritime Technical Working Group Focus on Fuel Switching: Fuel Oil Systems," July 24, 2007, available at http://www.arb.ca.gov/ports/marinevess/presentations/072407/072407herpres.pdf.

improve operational efficiency, and maintain the fuel circulation, injection, and combustion systems. These systems consist of storage and settling tanks, filters, and purifiers.

Fuel is transported from heated bunker tanks to the settling tank by transfer pumps. Settling tanks hold enough fuel for approximately 2 days of travel and have coils to heat the fuel, if heating is not maintained, the fuel will become too viscous to pump. In the settling tanks, heavy fuel solids settle to the bottom while fuel to be burned is drawn from the top of the tank. Fuel is then pumped from the settling tank through a pre-heater and into one or more centrifugal separators by feed pumps. This fuel is then pumped to the day tank, where approximately one day's reserve of pre-treated and cleaned fuel is maintained at an appropriate temperature to maintain fuel viscosity for use in the engine. The engine fuel supply system then draws fuel beyond that necessary for combustion from the day tank to the injection system and circulates the additional fuel back to the day tank to prevent solidification throughout the supply system. Sets of supply and circulating pumps pressurize the system and transfer fuel from the day tank, the final engine fuel filter, and injectors while a pre-heater and viscosity meter maintain fuel viscosity throughout the fuel system. Figure 2-12 shows a typical shipboard fuel delivery system. Figure 2-13 shows a fuel system as a layout onboard the vessel.

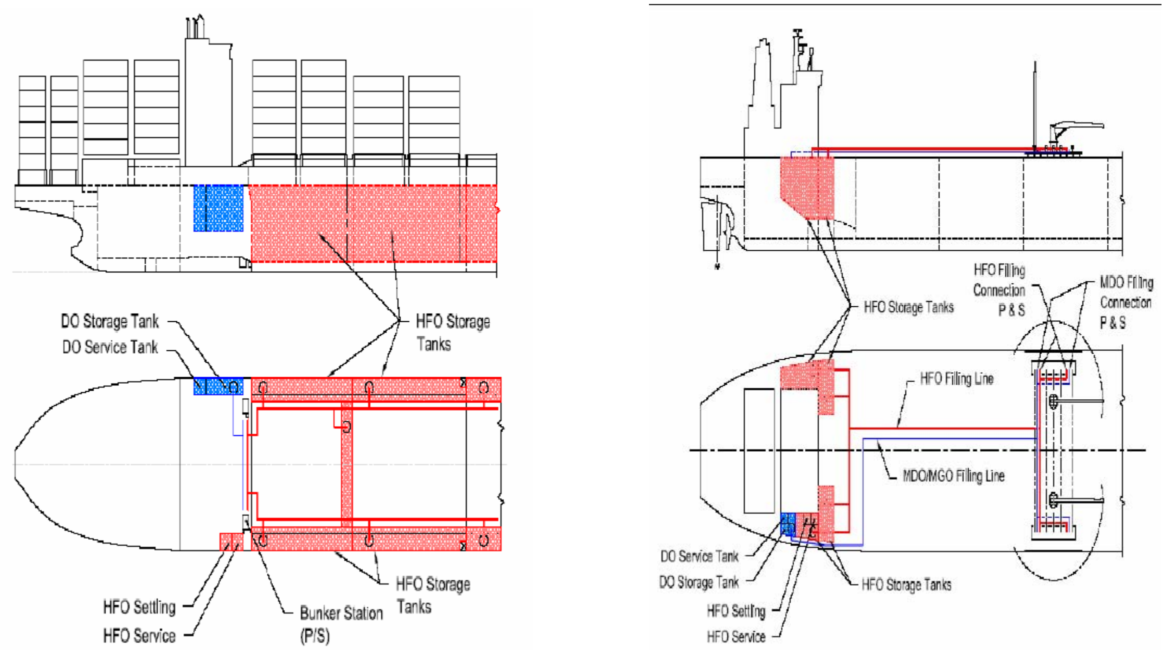
Figure 2-13. Typical Shipboard Unifuel Delivery System



Source: RTI International[33]

Figure 2-14. Typical Fuel Tank and Delivery Systems

Containership **Tanker**



Source: Herbert Engineering Corp[36]

2.3.2. Potential vessel modifications associated with fuel switching

Technical concerns regarding use of low-sulfur distillate fuels in Category 3 vessel engines relate to either steady-state operation on distillate fuels or the process of switching fuels.

Steady-state distillate fuel use may raise issues of cylinder lubricants and feed rates and fuel viscosity and temperature control. Low-speed, 2-stroke engines inject lubricating oil into the fuel prior to combustion, potentially requiring separate fuel-feed systems to implement fuel switching so that the proper oil is used with the fuel in use. Cylinder lubricating oils contain alkaline additives to counteract the acidity caused by sulfur oxides and must be mated appropriately to the sulfur content of the fuel used to control the deposition of acids in the cylinders and reduce wear. Wärtsilä recommends use of 70 base number (BN) cylinder oil when using fuels with 1.5 percent or more sulfur and 40BN oil for fuels with lower sulfur levels.[37] During periods of fuel switching, the BN to sulfur ratio (BN/S) can be out of balance. While unbalanced BN/S ratios cause excess engine wear, it is believed that changing lube oil is only necessary if the engines are to operate on fuel that is 1 percent sulfur or less for more than one week.[38] For longer periods, ships may require two cylinder lubricating oil systems. However, there is an oil that has

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[36] Herbert Engineering Corp., http://www.arb.ca.gov/ports/marinevess/presentations/072407/072407herpres.pdf

[37] Wärtsilä Switzerland Ltd, LOW SULPHUR GUIDELINES: Guidelines for design, modification and operation of new buildings and existing ships to comply with future legislation related to low sulphur content in the fuel, Updated: 9th January, 2006. Available at: http://www.wartsila.com/Wartsila/global//docs/en/ship_power/media_publications/technical_papers/low_sulphur_guidelines.pdf.

[38] MAN B&W, Operation on Low-Sulphur Fuels Two-Stroke Engines, available at: http://www.manbw.com/article_005271.html.

been recently developed for use with distillate or residual, so this might not be the case anymore.

In addition to BN/S matching, long term use of distillate fuels must consider viscosity matches between the fuel and the injection system design, as MDO and MGO are significantly less viscous than HFO. Although use of low viscosity fuels in medium speed, 4-stroke engines is generally not a concern, severe cases may lead to damaged fuel injection equipment and power loss. For low-speed, 2-stroke engines viscosity effects are typically minor, but may be affiliated with failed fuel treatment system pumps. Both cases may be mitigated by installation and use of a fuel cooler, associated piping, and viscosity meters to the fuel treatment system if fuel switching is done on a frequent basis.

Although all the above mentioned concerns are legitimate, it should be noted that in its presentation to ARB, Maersk[39] illustrated that all its vessels switch both main and auxiliary engines to MDO with less than 0.2 percent sulfur within 24 nautical miles of their California destination port for main engines and within 24 nautical miles of the California border for auxiliary engines. They have noted no problems to date on their vessels from this program.

The Maersk study included 78 vessels and 298 switches consuming 23.9 MT of MDO per switch from April 2006 to April or May 2007. The resulting total emissions reduction has been calculated at 800 tons per year, including a 95 percent SOx, 87 percent PM, and 12 percent NOx reduction (which includes low-NOx auxiliary mode). These reductions are greater than anticipated by the program. In the Maersk study, all vessels used separate service tanks for high- and low-sulfur fuels (DMA and DMB, with DMX for lifeboat engines and emergency generator use) to minimize compatibility issues. Also, as all fuel switching in this program is considered short term, they made no cylinder lube oil BN change. Maersk noted that fuel switching is considered “normal engineering practice” and provides no special training.

Some ships may not have sufficient onboard storage capacity to accommodate temporary fuel switching since the minimum space practical is devoted to fuel and machinery to maximize cargo and, of the space devoted to fuel, a minimal amount is provided for distillate oil tanks on unifuel ships. Some dual fuel ships have two fuel oil tank systems—one for residual and one for lower sulfur distillate oil. This arrangement may be preferred for fuel switching, since it avoids many issues with using dissimilar fuels in the same fuel system while still meeting lower sulfur requirements. The common arrangement is for one HFO tank system with multiple HFO tanks and associated fuel system and another distillate oil system with one or more MDO or MGO storage tanks and a corresponding day tank.

At their presentation to ARB, Herbert Engineering[36] surveyed a range of vessels and their ability to switch fuels. They found that, for tanker ships varying from a 50,000 DWT Panamax to a 300,000 DWT VLCC (Very Large Crude Carrier) vessels, while the HFO capacity and number of tanks and ancillary system components varied, the total capacity for distillate fuels remained at one settling and one service tank of varying volume with sufficient capacity for between 3.3 and 3.6 days operating range using distillate fuels in both main and auxiliary engines and in at-sea cruising mode with a 15 percent reserve. Typical containerships profiled ranged from a 2,500 TEU Feedership to a 9,000 TEU Post-Panamax containership. All cases have one storage tank and one service tank for distillate fuels except the largest containership, which had two storage tanks and one distillate service tank. Again, while total distillate storage volumes varied, the at-

[39] Maersk Pilot Fuel Switch Initiative, A.P. Moller-Maersk Group, Regulatory Affairs Technical Organisation, 26 July 2007, available at http://www.arb.ca.gov/ports/marinevess/presentations/072407/072407maepres.pdf.

sea cruising range using distillate fuels in both the main and auxiliary systems varied from 1.7 to 2.6 days. This study concluded that existing distillate oil tank capacities should be sufficient to accommodate main and auxiliary engine operation in SECAs. Typical onboard storage volumes and number of tanks by fuel type are shown in Table 2-7.

Table 2-7. Typical on-board storage for heavy fuel oil and distillate fuels by vessel type

Ship Type/Size	Tank Description	Volume (m^3)	Tank Description	Volume (m^3)
Container Vessels				
2500 TEU Feedership	6 HFO Storage +1 Settling +1 Storage	3,200	1 DO Storage +1 Service	300
4000 TEU Panamax Containership	8 HFO Storage +1 Settling +1 Storage	7,000	1 DO Storage +1 Service	350
6000 TEU Post-Panamax Containership	10 HFO Storage +2 Settling +1 Storage	8,000	1 DO Storage +1 Service	400
9000 TEU Post-Panamax Containership	12 HFO Storage +2 Settling +2 Storage	10,000	2 DO Storage +1 Service	800
Tanker Vessels				
50,000 DWT Panamax Tanker	2 HFO Storage +1 Settling +1 Storage	1,500	1 DO Storage +1 Service	150
110,000 DWT Aframax Tanker	4 HFO Storage +1 Settling +1 Storage	3,000	1 DO Storage +1 Service	250
160,000 DWT Suezmax Tanker	4 HFO Storage +1 Settling +1 Storage	4,000	1 DO Storage +1 Service	350
300,000 DWT VLCC	4 HFO Storage +2 Settling +1 Storage	5,500	1 DO Storage +1 Service	450

Source: Herbert Engineering Corp. [36]

Fuel use for a typical call for an average container ship and an average tanker are shown in Table 2-8 as a function of ECA distance from shore. Assuming the typical container ship is a 4000 TEU Panamax and the typical tanker is a 110,000 DWT Aframax, current fuel storage of distillate fuel is 343 metric tonnes and 245 metric tonnes respectively based upon a MGO fuel density of 980 kg/m^3. Thus even if the ECA is set at 200 nautical miles, a typical ship can make three to four calls into and out of a port before needing to refuel with existing distillate tanks. It should be noted that the fuel amounts in Table 2-8 represent average vessels, therefore, some vessels may require additional capacity to accomplish fuel switching.

Table 2-8. Fuel Use per Call for Various ECA Distances (Metric Tonnes)

ECA Distance	Container	Tanker
25	25.10	19.98
50	35.31	25.46
100	55.74	36.44
200	96.59	58.40

If a new or segregated tank is desired, ancillary equipment such as pumps, piping, vents, filing pipes, gauges, and access would be required, as well as tank testing.[40] In addition, fuel processing systems include settling tanks, filters, and centrifuges may also be necessary. While some vessel operators may be able to use their existing processing systems, other operators have reported that they will need to add to these systems, along with increased fuel capacity or other modifications.[41]

Also, should full-time switching from the use of high- to low-sulfur fuels be implemented, the Herbert Engineering study concluded that existing engines and fuel oil systems are suitable for continuous operation on distillate fuels, although will require use of lubricating oil with a different BN.

2.3.3. Modifications for fuel switching

In its March 2008 presentation,[42] ARB documented results from its 2006 vessel survey. ARB's results showed that approximately 22 percent of vessels surveyed needed some modifications to adequately perform main engine fuel switching, but the modifications needed and vessels requiring the modifications varied both with distance and vessel type. For main engine fuel switching, the required modifications included:

- Fuel tanks
- Cylinder lube oil systems
- Fuel valves
- Fuel piping and pumps
- Engine fuel pumps
- Fuel injectors

The ARB survey also found that 94 percent of vessels could participate in an auxiliary engine-only fuel switching program without any modifications. Of those that did require modifications, the required retrofits included the following:

- Fuel oil system
- Fuel tanks and lines
- Fuel injection/oil pump modifications
- Fuel oil micronizer
- Storage tanks
- Diesel fuel cooler
- Change lube oil BN and add cooling lines for fuel oil pumps

[40] Entec UK Limited. Quantification of Emissions from Ships Associated with Ship Movements between Ports in the European Community, July 2002, pps. 86-87.

[41] Air Resources Board, "Fuel Sulfur And Other Operational Requirements For Ocean-Going Vessels Within California Waters And 24 Nautical Miles Of The California Baseline – Initial Statement of Reasoning," June 2008.

[42] 2006 Ocean-Going Vessel Survey Results, Cal EPA Air Resources Board, 4th Public Workshop to Discuss Development of Regulations for Ocean-going Ship Main Engines and Auxiliary Boilers, March 5, 2008, Sacramento, CA.

A small number of survey participants reported the need to modify engine components such as fuel pumps, injectors, and nozzles. However, engine manufacturers have stated that, with certain caveats, the engines they designed for heavy fuel oil can also operate on MGO without these modifications.[41] In most cases, the need for fuel injection pumps and nozzles arises from the fact that older ship engines used nitrile rubber seals and o-rings which are susceptible to shrinking when a hydrogenated lower sulfur distillate fuel is used after running for long periods on heavy fuel oils. This causes leaks in both the fuel injector pumps and nozzles. Newer pumps and injectors use Viton® o-rings, which are much less susceptible to fuel changes. In some cases, replacement of old o-rings and seals will be necessary as an early maintenance item to prevent problems.

2.3.4. Scenarios analyzed and cost methodology

Three fuel switching cases are analyzed here for costs in Section 3, namely:

- Case 0: Vessels meet all requirements of a ECA and require no modifications or retrofits (baseline).
- Case 1: A newly built vessel requires additional equipment to meet ECA requirements over comparable new vessels.
- Case 2: Existing vessels will require retrofits to meet ECA requirements.

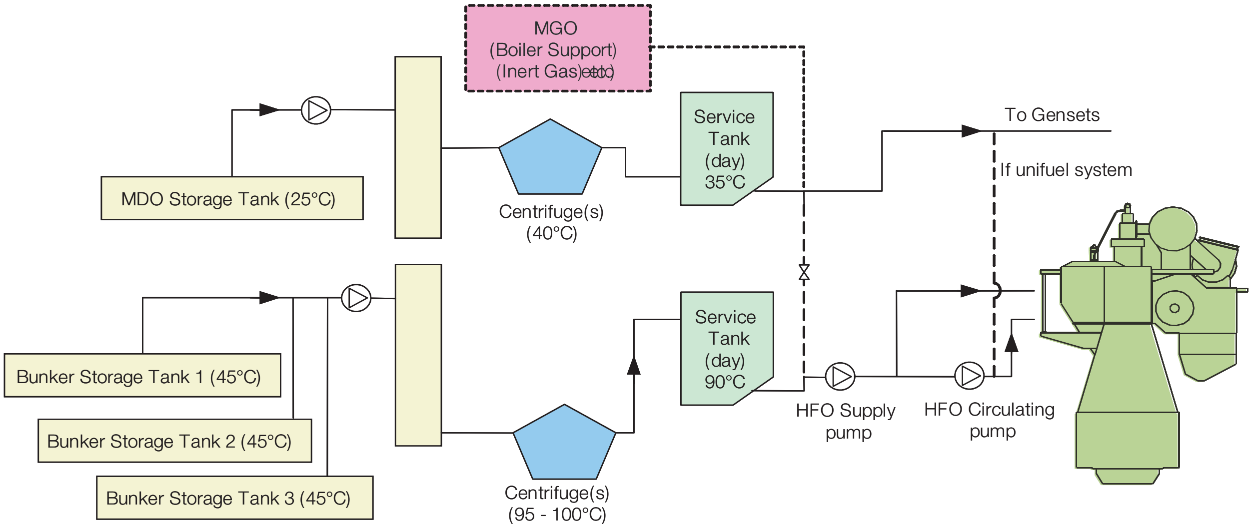
In all cases here, we have assumed that both propulsion and auxiliary engines will operate on the same distillate fuel when near the coastline for a continuous period of less than 1 week and that the distillate fuel will be 0.1 percent sulfur MGO. This analysis does not attempt to determine the number of ships that would require these modifications.

As discussed above, for short periods of operation on lower sulfur fuel for low speed, 2-stroke engines, a switch to lower cylinder lube oil TBN is not necessary. We have assumed that within the one week period considered here is within that range. Note that this switch is not applicable to 4-stroke engines.

We have based all calculations on the estimate that any retrofit distillate tanks would be designed to hold 250 hours of fuel under normal operation. This is larger than is currently available on most ships that currently carry distillate fuel as noted in the Herbert Engineering presentation (see Table 2-7). In building these tanks, we have assumed that they will be composed of cold rolled steel 1 mm thick and double walled.

Because fuel treatment systems vary by vessel and the fuel switching program will vary with the vessel treatment system, characterizing general costs is difficult. However, most ships have distillate systems onboard, although fuel switching may require modifications to accommodate the distillate usage envisioned here. The system envisioned here is most like MAN B&W's *Fuel Oil System No. 1* with one distillate and one heavy fuel oil settling tank, shown by Figure 2-14. Here, both HFO and MDO have a dedicated bunkering, settling, centrifuging, and service tank system. The distillate and residual systems are independent until fuel supply pressurization, and the injection systems are shared. If MGO is used instead, the settling tank and centrifuge might not be necessary.

Figure 2-15. MAN B&W's Fuel Oil System No. 1



Source: MAN B&W[38]

3. Economic Impact

3.1. Cost Estimation Methodology

In order to determine the estimated cost of compliance with potential future emission regulations, representative models of low- and medium-speed Category 3 marine diesel engines were chosen among several manufacturers' engine lines and costs were estimated for each. No single model's costs were used to develop the estimates presented in this report. Once cost information was developed, cost spreadsheets were shared with engine and emission control equipment manufacturers for comment. Presented costs for each technology represent a best estimate based upon all the input received.

Costs for the technologies discussed in Section 2 are presented in this section. These costs include hardware costs and fixed costs. Costs for changes in fuel consumption are also discussed. All costs represent the incremental costs for engines to meet the proposed emission standards.

Typically, Category 3 engines and emission reduction technologies are built outside the United States. All costs have been converted to 2006 U.S. dollars.

3.1.1. Hardware Cost to Manufacturer

Component costs were developed for each technology discussed in Section 2. Separate costs were derived for each of the various engines shown in Table 2-2. Manufacturer costs of components were estimated from various sources including information from marine diesel engine manufacturers, and previous work performed by the author of this document.[43] Labor rates used in this study were taken from Salary.com[44] for New Jersey and include a 60 percent fringe rate as shown in Table 3-1.

Table 3-1. Labor Rates

Labor Category	Annual Salary	60% Fringe	Annual Rate	Hourly Rate
Design Engineer II	$75,000	$45,000	$120,000	$57.69
Mechanic Technician II	$50,000	$30,000	$80,000	$38.46
Floor Assembler II	$31,000	$18,600	$49,600	$23.85

Hardware costs provided by a supplier other than the engine manufacturer are subject to a 29 percent mark up, which represents an average supplier mark up of technologies on new engine sales.[45]

3.1.2. Fixed Cost to Manufacturer

The fixed costs to the manufacturer consist of the cost of researching, developing and testing a new technology. They also include the cost of retooling for the production of new parts. Research and development costs reflect the need for manufacturers to focus on adapting

[43] L.Browning and R. Barnitt, "Emission Reduction Technology Costs for Category 3 Marine Diesel Engines," April 2002.

[44] http://www.salary.com

[45] Jack Faucett Associates, "Update of EPA's Motor Vehicle Emission Control Equipment Retail Price Equivalent (RPE) Calculation Formula," Report No. JACKFAU-85-322-3, September 1985.

emission controls to specific marine diesel engine applications, with significant engine calibration needed to optimize these controls over a large range of ship types and operating conditions.

Each year of research and development has been defined as 1 engineer and 2 technicians plus 24 engine tests per year at $10,000 per test. Total R&D costs per year are shown in Table 4-1.

Table 3-2. Annual Research and Development Costs

1 engineer	$120,000
2 technician	$160,000
40% overhead	$168,000
24 Tests @ $10,000 per test	$240,000
	$688,000

In addition, a $5,000 fee is added for Marine Society approval of the technology. All real costs calculated in this report are in 2006 dollars with future costs discounted at 7 percent per annum. R&D costs are expected to occur over a three year period ending one year prior to engine production. Tooling costs are expected to occur one year prior to engine production. Both R&D and tooling costs are expected to be recovered over the first five years of engine sales. Cost of money was assumed to be 7 percent per annum for these calculations. The estimated number of units per year was supplied by EPA.

3.1.3. Fuel Economy

As discussed in Section 2, many of the technologies can lead to either a fuel cost savings or cost penalty for the user. An estimate of these changes in fuel consumption is developed in this report by using engine characteristics such as brake specific fuel consumption (BSFC) and load factors.

The BSFC used in the analysis is listed in Table 2-2. For an average call, assuming that the Emission Control Area (ECA) starts 200 nautical miles (nm) from U.S. shores, average load factors for propulsion and auxiliary engines are given in Table 3-3.

Table 3-3. Average Load Factors

Mode	Speed (knots)	One-Way Distance (nm)	Time per Call (Hours)	Propulsion Load Factor	Auxiliary Load Factor
Cruise	17.4	200	23.0	83%	19%
Transit	12	12	2.0	27%	30%
Maneuver	5	5	2.0	2%	51%
Hotel	--	--	55.5		35%
Total/Average			82.4	73%	31%

Using the following formula, an estimate of the yearly fuel consumption for a 1% change in fuel consumption is determined. Actual fuel use can be scaled from this value using the ratio of actual fuel consumption change to the 1% change calculated here.

Annual Fuel Use = (Avg BSFC) * (Nominal hp) * (Load Factor) * (Annual hr of operation)

3.2. Retrofit Tier I Technology Costs

The costs for the retrofit kit include new fuel injectors plus 3 months R&D to modify timing. A Marine Society approval certificate is also included. As part of the IMO regulations, the retrofit kit cannot exceed $375 Special Drawing Rights (SDR)/metric tonne of NOx reduced. The currency value of the SDR is determined by summing the values in U.S. dollars, based on market exchange rates, of a basket of major currencies (the U.S. dollar, Euro, Japanese yen, and pound sterling). The SDR currency value is calculated daily and the valuation basket is reviewed and adjusted every five years. Current conversion rates are $1.49129 per SDR. As can be seen from Table 3-4, the cost effectiveness of the retrofit kits described above are significantly less than the maximum cost allowed in Annex VI.

Table 3-4. Cost of Retrofit Kits

Speed	**Medium**	**Low**	**Low**	**Low**
Engine Power (kW)	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**16**	**6**	**8**	**12**
Liters/cylinder	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**500**	**130**	**110**	**100**
Hardware Cost to Engine Manufacturer				
Component Costs				
Number of Injectors	16	18	24	36
Improved Fuel Valves (each)	$235	$235	$375	$470
Total Component Cost	**$3,760**	**$4,230**	**$9,000**	**$16,920**
Assembly				
Labor (hours)	120	168	216	312
Cost ($23.85/hr)	$2,862	$4,006	$5,151	$7,440
Overhead @ 40%	$1,145	$1,602	$2,060	$2,976
Total Assembly Cost	**$4,006**	**$5,609**	**$7,211**	**$10,416**
Total Variable Cost	**$7,766**	**$9,839**	**$16,211**	**$27,336**
Markup @ 29%	$2,252	$2,853	$4,701	$7,927
Total Hardware RPE	**$10,018**	**$12,692**	**$20,912**	**$35,263**
Fixed Costs				
R&D Costs (0.25 year R&D)	$172,000	$172,000	$172,000	$172,000
Marine Society Approval	$5,000	$5,000	$5,000	$5,000
Engines/yr.	40	40	40	40
Years to recover	5	5	5	5
Fixed cost/engine	**$1,233**	**$1,233**	**$1,233**	**$1,233**
Total Costs	**$11,251**	**$13,925**	**$22,145**	**$36,496**
Cost/kW	$0.6	$1.6	$1.5	$0.8
Estimated Emission Reduction (MT NOx)	638.67	389.92	688.09	2,201.89
Cost Effectiveness (SDR/MT NOx)	$11.8	$23.8	$21.5	$11.1

For estimated emission reduction, emission reductions are calculated at 11 percent of baseline emissions for 6000 hours per year for 5 years with a load factor of 0.768. Baseline NOx emission rates are 14 g/kWh for medium speed engines and 18.1 g/kWh for slow speed engines. Emission reductions in metric tonnes are thus calculated as follows:

Slow Speed Engines: 18.1 g/kWh x Power (kW) x 0.768 x 6000 hours/yr x 5 years/1000000 g/metric tonne x 11%

Medium Speed engines: 14 g/ kWh x Power (kW) x 0.768 x 6000 hours/yr x 5 years/1000000 g/metric tonne x 11%

3.3. Tier II Technology Costs

As discussed in Section 2, Tier II technology costs include engine modification costs and common rail fuel injection system costs. Engine modification costs to meet proposed Tier II emission levels are given in Table 3-5. These costs include modification of fuel injection timing, increasing the compression ratio, fuel injection nozzle optimization and Miller cycle effects. Retooling costs include cylinder head and piston rod shim modifications to increase compression ratios as well as to accommodate different injection nozzles.

Table 3-5. Differential Costs for Engine Modifications to Meet Tier II Emission Levels

Engine Speed	**Medium**	**Medium**	**Medium**	**Low**	**Low**	**Low**
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Fixed Costs						
R&D Costs (1 year R&D)	$688,000	$688,000	$688,000	$688,000	$688,000	$688,000
Retooling Costs	$500,000	$750,000	$1,000,000	$750,000	$1,000,000	$1,250,000
Marine Society Approval	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000
Engines/yr.	40	40	40	40	40	40
Years to recover	5	5	5	5	5	5
Fixed cost/engine	**$8,103**	**$9,734**	**$11,365**	**$9,734**	**$11,365**	**$12,996**
Total Costs	**$8,103**	**$9,734**	**$11,365**	**$9,734**	**$11,365**	**$12,996**
Cost per kW	$1.8	$1.0	$0.6	$1.1	$0.8	$0.3

Differential costs for new common rail fuel injection engines that replace engines that were mechanically injected are given in Table 3-6. Differential costs for common rail fuel injection engines that replace engine that were previously electronically controlled are given in Table 3-7. Retooling costs include modification of the cylinder head to accommodate common rail fuel injection systems.

Table 3-6. Common Rail Fuel Injection Costs for Mechanically Injected Engines

Speed	**Medium**	**Medium**	**Medium**	**Low**	**Low**	**Low**
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Hardware Cost to Engine Manufacturer						
Component Costs						
Electronic Control Unit	$3,500	$3,500	$3,500	$5,000	$5,000	$5,000
Common Rail Accumulators (each)	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000
Number of Accumulators	3	6	8	9	12	18
Low Pressure Pump	$2,000	$3,000	$4,000	$2,500	$3,500	$4,500
High Pressure Pump	$3,500	$4,500	$6,000	$4,500	$6,000	$8,000
Modified injectors (each)	$2,500	$2,500	$2,500	$3,500	$3,500	$3,500
Number of injectors	9	12	16	18	24	36
Wiring Harness	$2,500	$2,500	$2,500	$3,000	$3,000	$3,000
Total Component Cost	**$40,000**	**$55,500**	**$72,000**	**$96,000**	**$125,500**	**$182,500**
Assembly						
Labor (hours)	120	160	200	200	250	300
Cost ($23.85/hr)	$2,862	$3,815	$4,769	$4,769	$5,962	$7,154
Overhead @ 40%	$1,145	$1,526	$1,908	$1,908	$2,385	$2,862
Total Assembly Cost	**$4,006**	**$5,342**	**$6,677**	**$6,677**	**$8,346**	**$10,015**
Total Variable Cost	**$44,006**	**$60,842**	**$78,677**	**$102,677**	**$133,846**	**$192,515**
Markup @ 29%	$12,762	$17,644	$22,816	$29,776	$38,815	$55,829
Total Hardware RPE	**$56,768**	**$78,486**	**$101,493**	**$132,453**	**$172,662**	**$248,345**
Fixed Costs						
R&D Costs (1 year R&D)	$688,000	$688,000	$688,000	$688,000	$688,000	$688,000
Retooling Costs	$1,000,000	$1,000,000	$1,000,000	$1,000,000	$1,000,000	$1,000,000
Marine Society Approval	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000
Engines/yr.	40	40	40	40	40	40
Years to recover	5	5	5	5	5	5
Fixed cost/engine	**$11,365**	**$11,365**	**$11,365**	**$11,365**	**$11,365**	**$11,365**
Total Costs	**$68,133**	**$89,850**	**$112,858**	**$143,818**	**$184,026**	**$259,710**
Cost per kW	$15.1	$9.5	$6.3	$16.9	$12.3	$5.4

Table 3-7. Common Rail Fuel Injection Costs for Electronic Engines

Speed	**Medium**	**Medium**	**Medium**	**Low**	**Low**	**Low**
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Hardware Costs to the Manufacturer						
Component Costs						
Electronic Control Unit	$500	$500	$500	$500	$500	$500
Common Rail Accumulators (each)	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000
Number of Accumulators	3	6	8	9	12	18
Low Pressure Pump	$1,000	$1,000	$1,000	$1,500	$1,500	$1,500
High Pressure Pump	$1,500	$1,500	$1,500	$2,000	$2,000	$2,000
Modified injectors (each)	$500	$500	$500	$750	$750	$750
Number of injectors	9	12	16	18	24	36
Wiring Harness	$500	$500	$500	$650	$650	$650
Total Component Cost	**$14,000**	**$21,500**	**$27,500**	**$36,150**	**$46,650**	**$67,650**
Assembly						
Labor (hours)	40	60	80	40	60	80
Cost ($23.85/hr)	$954	$1,431	$1,908	$954	$1,431	$1,908
Overhead @ 40%	$382	$572	$763	$382	$572	$763
Total Assembly Cost	**$1,335**	**$2,003**	**$2,671**	**$1,335**	**$2,003**	**$2,671**
Total Variable Cost	**$15,335**	**$23,503**	**$30,171**	**$37,485**	**$48,653**	**$70,321**
Markup @ 29%	$4,447	$6,816	$8,750	$10,871	$14,109	$20,393
Total Hardware RPE	**$19,783**	**$30,319**	**$38,920**	**$48,356**	**$62,762**	**$90,714**
Fixed Costs						
R&D Costs (0.5 year R&D)	$344,000	$344,000	$344,000	$344,000	$344,000	$344,000
Retooling Costs	$500,000	$500,000	$500,000	$500,000	$500,000	$500,000
Marine Society Approval	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000
Engines/yr.	40	40	40	40	40	40
Years to recover	5	5	5	5	5	5
Fixed cost/engine	**$5,698**	**$5,698**	**$5,698**	**$5,698**	**$5,698**	**$5,698**
Total Costs	**$26,700**	**$34,868**	**$41,535**	**$48,850**	**$60,018**	**$81,685**
Cost per kW	$5.9	$3.7	$2.3	$5.7	$4.0	$1.7

3.4. Tier III Technology Costs

As discussed in Section 2, several options have been discussed to meet proposed Tier III emission levels. These include engine modifications, fumigation, fuel emulsions, direct water injection, exhaust gas recirculation, selective catalytic reduction and seawater scrubbing. Fuel switching costs are discussed in Section 3.4.

3.4.1. Engine Modifications

Engine modifications to meet proposed Tier III emission levels include use of two stage turbochargers and electronic valve actuation. Table 3-8 shows incremental costs for engine modifications to meet the proposed Tier III emission levels. Retooling costs represent turbocharger redesign and valve actuation modifications.

Table 3-8. Differential Engine Modifications Costs to Meet Tier III Emission Levels

Speed	**Medium**	**Medium**	**Medium**	**Low**	**Low**	**Low**
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Hardware Costs to the Manufacturer						
Component Costs						
2 Stage Turbochargers (Incremental)	$16,250	$20,900	$46,750	$28,000	$42,000	$61,000
Electronic Intake Valves (each)	$285	$285	$285			
Intake Valves per Cylinder	2	2	2			
Electronic Exhaust Valves (each)	$285	$285	$285	$425	$425	$425
Exhaust Valves per Cylinder	2	2	2	4	4	4
Controller	$3,750	$3,750	$3,750	$3,750	$3,750	$3,750
Wiring	$2,800	$2,800	$2,800	$2,800	$2,800	$2,800
Total Component Cost	**$33,060**	**$41,130**	**$71,540**	**$44,750**	**$62,150**	**$87,950**
Markup @ 29%	$9,587	$11,928	$20,747	$12,978	$18,024	$25,506
Total Hardware RPE	**$42,647**	**$53,058**	**$92,287**	**$57,728**	**$80,174**	**$113,456**
Fixed Costs						
R&D Costs (1 year R&D)	$688,000	$688,000	$688,000	$688,000	$688,000	$688,000
Retooling Costs	$700,000	$1,000,000	$1,300,000	$1,000,000	$1,300,000	$1,650,000
Marine Society Approval	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000
Engines/yr.	40	40	40	40	40	40
Years to recover	5	5	5	5	5	5
Fixed cost/engine	**$9,407**	**$11,365**	**$13,322**	**$11,365**	**$13,322**	**$15,605**
Total Costs	**$52,055**	**$64,422**	**$105,608**	**$69,092**	**$93,495**	**$129,061**
Cost per kW	$11.6	$6.8	$5.9	$8.1	$6.2	$2.7

3.4.2. Fumigation

Fumigation costs include costs for the water storage tank, the humidifier, the heat exchanger and various pumps and piping and are shown in Table 3-9. Water tank cost details are shown in Table 3-10 and estimate storage of water for 250 hours of normal operation when operating in the emission control area (ECA). It is envisioned that the water tank is constructed of cold rolled steel 1 mm thick. Cold rolled steel prices are estimated at $686 per metric tonne and represent average steel prices in 2006.[46] Water usage costs are shown in Table 3-11 and are estimated assuming a cost of $0.25/gallon for distilled water. For systems that use seawater, these costs should not be considered. Retooling costs are for redesign of the air intake system.

[46] MEPS Steel Prices On-line at http://www.steelonthenet.com/prices.html.

Table 3-9. Fumigation Costs

Speed	Medium	Medium	Medium	Low	Low	Low
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Hardware Costs to the Manufacturer						
Component Costs						
Water Tank	$2,036	$3,253	$4,885	$2,775	$3,939	$8,071
Humidifier	$70,000	$120,000	$240,000	$190,000	$310,000	$700,000
Heat Exchanger	$37,500	$47,000	$56,000	$47,000	$56,000	$75,000
Pump/Piping	$5,600	$7,500	$9,500	$7,500	$9,500	$11,300
Total Component Cost	**$109,536**	**$170,253**	**$300,885**	**$239,775**	**$369,939**	**$783,071**
Assembly						
Labor (hours)	400	600	800	750	1000	1250
Cost ($23.85/hr)	$9,538	$14,308	$19,077	$17,885	$23,846	$29,808
Overhead @ 40%	$3,815	$5,723	$7,631	$7,154	$9,538	$11,923
Total Assembly Cost	**$13,354**	**$20,031**	**$26,708**	**$25,038**	**$33,385**	**$41,731**
Total Variable Cost	$122,890	$190,284	$327,592	$264,813	$403,323	$824,802
Markup @ 29%	$35,638	$55,182	$95,002	$76,796	$116,964	$239,192
Total Hardware RPE	**$158,528**	**$245,466**	**$422,594**	**$341,609**	**$520,287**	**$1,063,994**
Fixed Costs						
R&D Costs (1 year R&D)	$688,000	$688,000	$688,000	$688,000	$688,000	$688,000
Retooling Costs	$1,000,000	$1,000,000	$1,000,000	$1,000,000	$1,000,000	$1,000,000
Marine Society Approval	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000
Engines/yr.	40	40	40	40	40	40
Years to recover	5	5	5	5	5	5
Fixed cost/engine	**$11,365**	**$11,365**	**$11,365**	**$11,365**	**$11,365**	**$11,365**
Total Costs	**$169,892**	**$256,831**	**$433,959**	**$352,974**	**$531,652**	**$1,075,359**
Cost per kW	$37.8	$27.0	$24.1	$41.5	$35.4	$22.4

Table 3-10. Fumigation Water Tank Costs

Speed	Medium	Medium	Medium	Low	Low	Low
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Water Tank Costs						
Fuel Amount (kg)	240,996	508,769	963,984	422,699	745,940	2,387,008
Density (kg/m^3)	1,000	1,000	1,000	1,000	1,000	1,000
Tank Size (m^3)	289	611	1,157	423	746	2,387
Tank Material (m^3)	0.26	0.43	0.66	0.34	0.49	1.07
Tank Material Cost ($)	$1,411	$2,321	$3,553	$1,817	$2,653	$5,756
Assembly						
Labor (hours)	5	6	7	10	12	15
Cost ($23.85/hr)	$119	$143	$167	$238	$286	$358
Overhead @ 40%	$48	$57	$67	$95	$114	$143
Total Assembly Cost	$167	$200	$234	$334	$401	$501
Total Variable Cost	$1,578	$2,522	$3,787	$2,151	$3,053	$6,257
Markup @ 29%	$458	$731	$1,098	$624	$885	$1,814
Total Hardware RPE	$2,036	$3,253	$4,885	$2,775	$3,939	$8,071

Table 3-11. Fumigation Distilled Water Costs

Speed	Medium	Medium	Medium	Low	Low	Low
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Distilled Water Costs						
BSFC (g/kWh)	210	210	210	195	195	195
Load factor	73%	73%	73%	73%	73%	73%
Water/Fuel Ratio	1.40	1.40	1.40	1.40	1.40	1.40
Water Use (kg/hr)	964	2,035	3,856	1,691	2,984	9,548
Water Cost per kg	$0.0264	$0.0264	$0.0264	$0.0264	$0.0264	$0.0264
Water cost per hour	$25	$54	$102	$45	$79	$252

3.4.3. Fuel Emulsification

Fuel emulsification costs include costs for the water storage tank, the ultrasonic homogenizer, the heat exchanger, and various pumps and piping. These are shown in Table 3-12. Water tank cost details are shown in Table 3-13 and estimate storage of water for 250 hours of normal operation when operating in the emission control area (ECA). It is envisioned that the water tank is constructed of cold rolled steel 1 mm thick. Water usage costs are shown in Table 3-14 and are estimated assuming a cost of $0.25/gallon for distilled water. Retooling costs are for redesign of the fuel system to accommodate fuel emulsification.

Table 3-12. Fuel Emulsification Costs

Speed	**Medium**	**Medium**	**Medium**	**Low**	**Low**	**Low**
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Hardware Costs to the Manufacturer						
Component Costs						
Water Tank	$1,132	$1,767	$2,610	$1,611	$2,240	$4,386
Ultrasonic Homogenizer	$37,500	$56,000	$75,000	$56,000	$75,000	$112,200
Heat Exchanger	$9,400	$11,700	$14,000	$11,700	$14,000	$16,400
Pump/Piping	$4,700	$5,600	$6,600	$5,600	$6,600	$7,500
Total Component Cost	**$52,732**	**$75,067**	**$98,210**	**$74,911**	**$97,840**	**$140,486**
Assembly						
Labor (hours)	240	320	400	320	400	480
Cost ($23.85/hr)	$5,723	$7,631	$9,538	$7,631	$9,538	$11,446
Overhead @ 40%	$2,289	$3,052	$3,815	$3,052	$3,815	$4,578
Total Assembly Cost	**$8,012**	**$10,683**	**$13,354**	**$10,683**	**$13,354**	**$16,025**
Total Variable Cost	$60,745	$85,750	$111,564	$85,595	$111,194	$156,511
Markup @ 29%	$17,616	$24,867	$32,354	$24,822	$32,246	$45,388
Total Hardware RPE	**$78,361**	**$110,617**	**$143,918**	**$110,417**	**$143,441**	**$201,899**
Fixed Costs						
R&D Costs (1 year R&D)	$688,000	$688,000	$688,000	$688,000	$688,000	$688,000
Retooling Costs	$500,000	$500,000	$500,000	$500,000	$500,000	$500,000
Marine Society Approval	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000
Engines/yr.	40	40	40	40	40	40
Years to recover	5	5	5	5	5	5
Fixed cost/engine	**$8,103**	**$8,103**	**$8,103**	**$8,103**	**$8,103**	**$8,103**
Total Costs	**$86,463**	**$118,720**	**$152,020**	**$118,520**	**$151,543**	**$210,001**
Cost per kW	$19.2	$12.5	$8.4	$13.9	$10.1	$4.4

Table 3-13. Emulsification Water Tank Costs

Speed	Medium	Medium	Medium	Low	Low	Low
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Water Tank Costs						
Fuel Amount (kg)	86,070	181,703	344,280	150,964	266,407	852,503
Density (kg/m^3)	1,000	1,000	1,000	1,000	1,000	1,000
Tank Size (m^3)	103	218	413	151	266	853
Tank Material (m^3)	0.13	0.22	0.33	0.17	0.25	0.54
Tank Material Cost ($)	$711	$1,169	$1,790	$915	$1,336	$2,899
Assembly						
Labor (hours)	5	6	7	10	12	15
Cost ($23.85/hr)	$119	$143	$167	$238	$286	$358
Overhead @ 40%	$48	$57	$67	$95	$114	$143
Total Assembly Cost	$167	$200	$234	$334	$401	$501
Total Variable Cost	$878	$1,370	$2,023	$1,249	$1,737	$3,400
Markup @ 29%	$255	$397	$587	$362	$504	$986
Total Hardware RPE	$1,132	$1,767	$2,610	$1,611	$2,240	$4,386

Table 3-14. Emulsification Distilled Water Costs

Speed	Medium	Medium	Medium	Low	Low	Low
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Distilled Water Costs						
BSFC (g/kWh)	210	210	210	195	195	195
Load factor	73%	73%	73%	73%	73%	73%
Water/Fuel Ratio	0.50	0.50	0.50	0.50	0.50	0.50
Water Use (kg/hr)	344	727	1,377	604	1,066	3,410
Water Cost per kg	$0.0264	$0.0264	$0.0264	$0.0264	$0.0264	$0.0264
Water cost per hour	$9	$19	$36	$16	$28	$90

3.4.4. Direct Water Injection

Direct water injection costs include costs for the water storage tank, a low pressure module, a high pressure module, flow fuses, water injectors, related piping, and the control unit and wiring and are shown in Table 3-15. Water tank cost details are shown in Table 3-16 and estimate storage of water for 250 hours of normal operation when operating in the ECA. It is envisioned that the water tank is constructed of cold rolled steel 1 mm thick. Water usage costs are shown in Table 3-17 and are estimated assuming a cost of $0.25/gallon for distilled water. Retooling costs are for redesign of the cylinder head to accommodate the direct water injectors.

Table 3-15. Direct Water Injection Costs

Speed	Medium	Medium	Medium	Low	Low	Low
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Hardware Costs to the Manufacturer						
Component Costs						
Water Tank	$1,132	$1,767	$2,610	$1,611	$2,240	$4,386
Low Pressure Module	$4,700	$7,000	$9,500	$9,500	$19,000	$3,800
High Pressure Module	$9,500	$14,000	$19,000	$19,000	$38,000	$75,000
Flow Fuses (each)	$1,900	$1,900	$1,900	$1,900	$1,900	$1,900
Water Injectors (each)	$2,400	$2,400	$2,400	$2,400	$2,400	$2,400
Number per cylinder	1	2	3	3	6	12
Piping	$5,600	$7,500	$9,500	$9,500	$14,000	$19,000
Control Unit/Wiring	$9,500	$11,300	$13,000	$11,300	$13,000	$15,000
Total Component Cost	**$69,132**	**$144,767**	**$260,010**	**$128,311**	**$292,640**	**$736,386**
Assembly						
Labor (hours)	500	750	1000	1000	1500	2000
Cost ($23.85/hr)	$11,923	$17,885	$23,846	$23,846	$35,769	$47,692
Overhead @ 40%	$4,769	$7,154	$9,538	$9,538	$14,308	$19,077
Total Assembly Cost	**$16,692**	**$25,038**	**$33,385**	**$33,385**	**$50,077**	**$66,769**
Total Variable Cost	$85,825	$169,805	$293,395	$161,696	$342,717	$803,155
Markup @ 29%	$24,889	$49,244	$85,084	$46,892	$99,388	$232,915
Total Hardware RPE	**$110,714**	**$219,049**	**$378,479**	**$208,588**	**$442,105**	**$1,036,070**
Fixed Costs						
R&D Costs (2 years R&D)	$1,376,000	$1,376,000	$1,376,000	$1,376,000	$1,376,000	$1,376,000
Retooling Costs	$10,000,000	$10,000,000	$10,000,000	$10,000,000	$10,000,000	$10,000,000
Marine Society Approval	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000
Engines/yr.	40	40	40	40	40	40
Years to recover	5	5	5	5	5	5
Fixed cost/engine	**$74,891**	**$74,891**	**$74,891**	**$74,891**	**$74,891**	**$74,891**
Total Costs	**$185,605**	**$293,940**	**$453,371**	**$283,479**	**$516,997**	**$1,110,962**
Cost per kW	$41.2	$30.9	$25.2	$33.4	$34.5	$23.1

Table 3-16. DWI Water Tank Costs

Speed	**Medium**	**Medium**	**Medium**	**Low**	**Low**	**Low**
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Water Tank Costs						
Fuel Amount (kg)	86,070	181,703	344,280	150,964	266,407	852,503
Density (kg/m^3)	1,000	1,000	1,000	1,000	1,000	1,000
Tank Size (m^3)	103	218	413	151	266	853
Tank Material (m^3)	0.13	0.22	0.33	0.17	0.25	0.54
Tank Material Cost ($)	$711	$1,169	$1,790	$915	$1,336	$2,899
Assembly						
Labor (hours)	5	6	7	10	12	15
Cost ($23.85/hr)	$119	$143	$167	$238	$286	$358
Overhead @ 40%	$48	$57	$67	$95	$114	$143
Total Assembly Cost	$167	$200	$234	$334	$401	$501
Total Variable Cost	$878	$1,370	$2,023	$1,249	$1,737	$3,400
Markup @ 29%	$255	$397	$587	$362	$504	$986
Total Hardware RPE	$1,132	$1,767	$2,610	$1,611	$2,240	$4,386

Table 3-17. DWI Distilled Water Costs

Speed	**Medium**	**Medium**	**Medium**	**Low**	**Low**	**Low**
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Distilled Water Costs						
BSFC (g/kWh)	210	210	210	195	195	195
Load factor	73%	73%	73%	73%	73%	73%
Water/Fuel Ratio	0.50	0.50	0.50	0.50	0.50	0.50
Water Use (kg/hr)	344	727	1,377	604	1,066	3,410
Water Cost per kg	$0.0264	$0.0264	$0.0264	$0.0264	$0.0264	$0.0264
Water cost per hour	$9	$19	$36	$16	$28	$90

3.4.5. Exhaust Gas Recirculation

Exhaust gas recirculation costs include a supply pump, a sludge tank, piping, a waste pump, a recirculation pump, a scrubber unit, a separator, an EGR valve, and the control unit and wiring. Costs for an EGR system are given in Table 3-18. Retooling costs are for exhaust system redesign. Table 3-19 provide details on the sludge tank. Sludge is estimated to build up at 0.05 g/kWh with a sludge density of 1,300 kg/m^3 based upon an average 20 percent EGR rate. The sludge tank is envisioned to be constructed of cold rolled steel 1 mm thick. The tank will hold sludge generated from 500 hours of engine operation.

Table 3-18. Exhaust Gas Recirculation Costs

Speed	**Medium**	**Medium**	**Medium**	**Low**	**Low**	**Low**
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Hardware Costs to the Manufacturer						
Component Costs						
Supply Pump	$1,900	$2,600	$3,600	$2,600	$4,400	$7,000
Sludge Tank	$268	$345	$435	$511	$635	$859
Piping	$2,800	$3,800	$4,700	$3,700	$4,700	$5,600
Waste Pump	$1,900	$2,800	$3,800	$2,800	$4,700	$7,500
Recirculation Pump	$1,900	$2,800	$3,800	$2,800	$4,700	$7,500
Scrubber Unit	$23,500	$35,000	$56,000	$32,700	$56,000	$112,200
Separator	$1,900	$2,800	$3,800	$2,800	$3,800	$4,700
EGR Valve	$7,000	$9,500	$11,700	$9,500	$11,700	$14,000
Control Unit/Wiring	$4,700	$4,700	$4,700	$4,700	$4,700	$4,700
Total Component Cost	**$45,868**	**$64,345**	**$92,535**	**$62,111**	**$95,335**	**$164,059**
Assembly						
Labor (hours)	200	300	400	300	400	500
Cost ($23.85/hr)	$4,769	$7,154	$9,538	$7,154	$9,538	$11,923
Overhead @ 40%	$1,908	$2,862	$3,815	$2,862	$3,815	$4,769
Total Assembly Cost	**$6,677**	**$10,015**	**$13,354**	**$10,015**	**$13,354**	**$16,692**
Total Variable Cost	$52,545	$74,361	$105,888	$72,127	$108,689	$180,751
Markup @ 29%	$15,238	$21,565	$30,708	$20,917	$31,520	$52,418
Total Hardware RPE	**$67,783**	**$95,925**	**$136,596**	**$93,044**	**$140,208**	**$233,169**
Fixed Costs						
R&D Costs (1 year R&D)	$688,000	$688,000	$688,000	$688,000	$688,000	$688,000
Retooling Costs	$2,000,000	$2,000,000	$2,000,000	$2,000,000	$2,000,000	$2,000,000
Marine Society Approval	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000
Engines/yr.	40	40	40	40	40	40
Years to recover	5	5	5	5	5	5
Fixed cost/engine	**$17,889**	**$17,889**	**$17,889**	**$17,889**	**$17,889**	**$17,889**
Total Costs	**$85,672**	**$113,814**	**$154,485**	**$110,932**	**$158,097**	**$251,058**
Cost per kW	$19.0	$12.0	$8.6	$13.1	$10.5	$5.2

Table 3-19. Sludge Tank Costs

Speed	**Medium**	**Medium**	**Medium**	**Low**	**Low**	**Low**
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Sludge Tank Costs						
Sludge Rate, g/kWh	0.05	0.05	0.05	0.05	0.05	0.05
Sludge Amount (kg)	112.50	237.50	450.00	212.50	375.00	1,200.00
Sludge Tank size (m^3)	0.104	0.219	0.415	0.196	0.346	1.108
Tank Material (m^3)	0.01	0.01	0.02	0.01	0.01	0.03
Tank Material Cost ($)	$41	$67	$103	$63	$91	$198
Assembly						
Labor (hours)	5	6	7	10	12	14
Cost ($23.85/hr)	$119	$143	$167	$238	$286	$334
Overhead @ 40%	$48	$57	$67	$95	$114	$134
Total Assembly Cost	$167	$200	$234	$334	$401	$467
Total Variable Cost	$208	$268	$337	$396	$492	$666
Markup @ 29%	$60	$78	$98	$115	$143	$193
Total Hardware RPE	$268	$345	$435	$511	$635	$859

3.4.6. Selective Catalytic Reduction

Selective catalytic reduction (SCR) costs include the urea tank, the reactor, dosage pump, urea injectors, piping, bypass valve, the acoustic horn, a cleaning probe and the control unit and wiring. Detailed costs are shown in Table 3-20. Retooling costs are for redesign of the exhaust system to accommodate the SCR unit. Detailed costs for the urea tank are shown in Table 3-21 and estimate storage of urea for 250 hours of normal operation when operating in the emission control area (ECA). Because of the corrosive nature of urea, it is envisioned that the urea tank is constructed of 304 stainless steel 1 mm thick at a cost of $2,747.20 per metric tonne.[47] Urea usage costs are shown in Table 3-22 and are estimated assuming a cost of $1.52/gallon for urea with a density of 1.09 grams per cubic centimeter.

[47] http://www.metalprices.com/FreeSite/metals/stainless_product/product.asp#Tables for 2006.

Table 3-20. Selective Catalytic Reduction Costs

Speed	**Medium**	**Medium**	**Medium**	**Low**	**Low**	**Low**
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Hardware Costs to the Supplier						
Component Costs						
Aqueous Urea Tank	$1,194	$1,868	$2,765	$1,690	$2,356	$4,636
Reactor	$200,000	$295,000	$400,000	$345,000	$560,000	$1,400,000
Dosage Pump	$9,500	$11,300	$13,000	$11,300	$13,000	$15,000
Urea Injectors (each)	$2,400	$2,400	$2,400	$2,400	$2,400	$2,400
Number of Urea Injectors	3	6	8	12	16	24
Piping	$4,700	$5,600	$6,600	$5,600	$7,500	$9,500
Bypass Valve	$4,700	$5,600	$6,600	$5,600	$6,600	$7,500
Acoustic Horn	$9,500	$11,300	$13,000	$11,700	$14,000	$16,400
Cleaning Probe	$575	$575	$575	$700	$700	$700
Control Unit/Wiring	$14,000	$14,000	$14,000	$19,000	$19,000	$19,000
Total Component Cost	**$251,369**	**$359,643**	**$475,740**	**$429,390**	**$661,556**	**$1,530,336**
Assembly						
Labor (hours)	1000	1200	1500	1200	1600	2000
Cost ($23.85/hr)	$23,846	$28,615	$35,769	$28,615	$38,154	$47,692
Overhead @ 40%	$9,538	$11,446	$14,308	$11,446	$15,262	$19,077
Total Assembly Cost	**$33,385**	**$40,062**	**$50,077**	**$40,062**	**$53,415**	**$66,769**
Total Variable Cost	$284,753	$399,704	$525,816	$469,452	$714,971	$1,597,106
Markup @ 29%	$82,578	$115,914	$152,487	$136,141	$207,342	$463,161
Total Hardware RPE	**$367,332**	**$515,618**	**$678,303**	**$605,593**	**$922,313**	**$2,060,266**
Fixed Costs						
R&D Costs (2 years R&D)	$1,376,000	$1,376,000	$1,376,000	$1,376,000	$1,376,000	$1,376,000
Retooling Costs	$2,000,000	$2,000,000	$2,000,000	$2,000,000	$2,000,000	$2,000,000
Marine Society Approval	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000
Engines/yr.	40	40	40	40	40	40
Years to recover	5	5	5	5	5	5
Fixed cost/engine	**$22,699**	**$22,699**	**$22,699**	**$22,699**	**$22,699**	**$22,699**
Total Costs	**$390,031**	**$538,317**	**$701,002**	**$628,292**	**$945,012**	**$2,082,965**
Cost per kW	$86.7	$56.7	$38.9	$73.9	$63.0	$43.4

Table 3-21. Urea Tank Costs

Speed	**Medium**	**Medium**	**Medium**	**Low**	**Low**	**Low**
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Urea Tank Costs						
Urea Amount (kg)	12,910	27,255	51,642	22,645	39,961	127,875
Density (kg/m^3)	1,090	1,090	1,090	1,090	1,090	1,090
Tank Size (m^3)	14	30	57	21	37	117
Tank Material (m^3)	0.04	0.06	0.09	0.05	0.07	0.14
Tank Material Cost ($)	$758	$1,248	$1,909	$977	$1,426	$3,093
Assembly						
Labor (hours)	5	6	7	10	12	15
Cost ($23.85/hr)	$119	$143	$167	$238	$286	$358
Overhead @ 40%	$48	$57	$67	$95	$114	$143
Total Assembly Cost	$167	$200	$234	$334	$401	$501
Total Variable Cost	$925	$1,448	$2,143	$1,310	$1,826	$3,594
Markup @ 29%	$268	$420	$621	$380	$530	$1,042
Total Hardware RPE	$1,194	$1,868	$2,765	$1,690	$2,356	$4,636

Table 3-22. Urea Costs

Speed	**Medium**	**Medium**	**Medium**	**Low**	**Low**	**Low**
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Aqueous Urea Costs						
BSFC (g/kWh)	210	210	210	195	195	195
Load factor	73%	73%	73%	73%	73%	73%
Aqueous Urea Rate	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%
Aqueous Urea (kg/hr)	52	109	207	91	160	512
Aqueous Urea Cost per kg	$0.3684	$0.3684	$0.3684	$0.3684	$0.3684	$0.3684
Aqueous Urea Cost per hour	$19	$40	$76	$33	$59	$188

3.4.7. Sea Water Scrubbers

Sea water scrubber costs include the supply pump, the sludge tank, piping, a waste pump, a recirculation pump, the scrubber unit, an oil/water separator, an SO_2 monitor, and the control unit and wiring. Retooling costs are for redesign of the exhaust system to accommodate the scrubber unit. Detailed costs are given in Table 3-23. Detailed costs for the sludge tank are given in Table 3-24 and assume a sludge buildup rate of 0.25 g/kWh[48] and a sludge density of 1,300 kg/m^3. The sludge tank is envisioned to be constructed of cold rolled steel 1 mm thick. The tank will hold sludge generated for 500 hours of engine operation.

[48] Entec UK Ltd, "Service Contract on Ship Emissions: Assignment, Abatement and Market Based Instruments – Task 2c – SO_2 Abatement," August 2005 available at http://ec.europa.eu/environment/air/pdf/task2_so2.pdf.

Table 3-23. Sea Water Scrubber Costs

Speed	**Medium**	**Medium**	**Medium**	**Low**	**Low**	**Low**
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Hardware Costs to the Supplier						
Component Costs						
Supply Pump	$9,500	$14,000	$19,000	$14,000	$23,500	$37,500
Sludge Tank	$350	$481	$641	$637	$818	$1,256
Piping	$4,700	$5,600	$6,600	$5,600	$7,500	$9,500
Waste Pump	$9,500	$11,300	$13,000	$11,300	$13,000	$15,000
Recirculating Pump	$9,500	$11,300	$13,000	$11,300	$13,000	$15,000
Scrubber Unit	$215,000	$355,000	$550,000	$340,000	$500,000	$1,125,000
Separator	$7,000	$8,000	$9,000	$8,000	$9,000	$10,000
SO2 Monitor	$9,500	$9,500	$9,500	$9,500	$9,500	$9,500
Control Unit/Wiring	$28,000	$28,000	$28,000	$28,000	$28,000	$28,000
Total Component Cost	**$293,050**	**$443,181**	**$648,741**	**$428,337**	**$604,318**	**$1,250,756**
Assembly						
Labor (hours)	600	800	1000	1000	1500	2000
Cost ($23.85/hr)	$14,308	$19,077	$23,846	$23,846	$35,769	$47,692
Overhead @ 40%	$5,723	$7,631	$9,538	$9,538	$14,308	$19,077
Total Assembly Cost	**$20,031**	**$26,708**	**$33,385**	**$33,385**	**$50,077**	**$66,769**
Total Variable Cost	$313,081	$469,888	$682,126	$461,722	$654,395	$1,317,525
Markup @ 29%	$90,794	$136,268	$197,817	$133,899	$189,774	$382,082
Total Hardware RPE	**$403,875**	**$606,156**	**$879,943**	**$595,621**	**$844,169**	**$1,699,608**
Fixed Costs						
R&D Costs (1 year R&D)	$688,000	$688,000	$688,000	$688,000	$688,000	$688,000
Retooling Costs	$2,000,000	$2,000,000	$2,000,000	$2,000,000	$2,000,000	$2,000,000
Marine Society Approval	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000
Engines/yr.	40	40	40	40	40	40
Years to recover	5	5	5	5	5	5
Fixed cost/engine	**$17,889**	**$17,889**	**$17,889**	**$17,889**	**$17,889**	**$17,889**
Total Costs	**$421,763**	**$624,045**	**$897,831**	**$613,510**	**$862,058**	**$1,717,497**
Cost per kW	$93.7	$65.7	$49.9	$72.2	$57.5	$35.8

Table 3-24. Sludge Tank Costs

Speed	**Medium**	**Medium**	**Medium**	**Low**	**Low**	**Low**
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Sludge Tank Costs						
Sludge Rate, g/kWh	0.25	0.25	0.25	0.25	0.25	0.25
Sludge Amount (kg)	562.50	1,187.50	2,250.00	1,062.50	1,875.00	6,000.00
Sludge Tank size (m^3)	0.519	1.096	2.077	0.981	1.731	5.538
Tank Material (m^3)	0.02	0.03	0.05	0.03	0.04	0.09
Tank Material Cost ($)	$105	$172	$264	$160	$233	$506
Assembly						
Labor (hours)	5	6	7	10	12	14
Cost ($23.85/hr)	$119	$143	$167	$238	$286	$334
Overhead @ 40%	$48	$57	$67	$95	$114	$134
Total Assembly Cost	$167	$200	$234	$334	$401	$467
Total Variable Cost	$272	$372	$497	$494	$634	$974
Markup @ 29%	$79	$108	$144	$143	$184	$282
Total Hardware RPE	$350	$481	$641	$637	$818	$1,256

3.5. Fuel Switching Hardware Costs

In this section, hardware costs related to fuel switching are discussed. Fuel cost differentials have been discussed in another EPA report.[33] Three cases are discussed in Section 2.3, namely:

- Case 0: Vessels meet all requirements of a ECA and require no modifications or retrofits (baseline).
- Case 1: A newly built vessel requires additional equipment to meet ECA requirements over comparable new vessels.
- Case 2: Existing vessels will require retrofits to meet ECA requirements.

Case 0 assumes that the vessels have sufficient storage tank capacity currently for fuel switching and all the proper equipment necessary to accomplish fuel switching in a ECA area. Based upon their survey, ARB estimates that 78 percent of all ships fall into this category. However, ARB believes that this is an underestimation and that the vast majority of ships fall into this category.[41] There is no hardware costs associated with Case 0.

Case 1 assumes that new vessels will be built with additional distillate fuel storage capacity and systems over existing ships. Costs include additional distillate fuel storage tanks, an LFO fuel separator, an HFO/LFO blending unit, a 3-way valve, an LFO cooler, filters, a viscosity meter, and various pumps and piping. These costs are shown in Table 3-25. Details on additional tank costs are shown in Table 3-26. Distillate tanks are assumed to be constructed of cold rolled steel 1 mm thick and double walled and will hold an additional 250 hours of propulsion and auxiliary engine operation while within a ECA.

Table 3-25. Case 1 Fuel Switching Costs (New Construction)

Speed	**Medium**	**Medium**	**Medium**	**Low**	**Low**	**Low**
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Hardware Cost to Supplier						
Component Costs						
Additional Tanks	$3,409	$5,511	$8,341	$4,562	$6,548	$13,733
LFO Separator	$2,800	$3,300	$3,800	$3,800	$4,200	$4,700
HFO/LFO Blending Unit	$4,200	$4,700	$5,600	$4,700	$5,600	$6,600
3-Way Valve	$950	$1,400	$1,900	$1,400	$1,900	$2,800
LFO Cooler	$2,400	$2,800	$3,300	$2,800	$3,800	$4,700
Filters	$950	$950	$950	$950	$950	$950
Viscosity Meter	$1,400	$1,400	$1,400	$1,400	$1,400	$1,400
Piping/Pumps	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000
Total Component Cost	**$18,109**	**$22,061**	**$27,291**	**$21,612**	**$26,398**	**$36,883**
Assembly						
Labor (hours)	240	320	480	320	480	600
Cost ($23.85/hr)	$5,723	$7,631	$11,446	$7,631	$11,446	$14,308
Overhead @ 40%	$2,289	$3,052	$4,578	$3,052	$4,578	$5,723
Total Assembly Cost	**$8,012**	**$10,683**	**$16,025**	**$10,683**	**$16,025**	**$20,031**
Total Variable Cost	$26,121	$32,744	$43,316	$32,295	$42,423	$56,914
Markup @ 29%	$7,575	$9,496	$12,562	$9,366	$12,303	$16,505
Total Hardware RPE	**$33,696**	**$42,240**	**$55,877**	**$41,661**	**$54,725**	**$73,419**
Fixed Costs						
R&D Costs (0.25 year R&D)	$172,000	$172,000	$172,000	$172,000	$172,000	$172,000
Marine Society Approval	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000
Engines/yr.	40	40	40	40	40	40
Years to recover	5	5	5	5	5	5
Fixed cost/engine	**$1,233**	**$1,233**	**$1,233**	**$1,233**	**$1,233**	**$1,233**
Total Costs	**$34,929**	**$43,473**	**$57,110**	**$42,894**	**$55,958**	**$74,652**
Cost per kW	$7.8	$4.6	$3.2	$5.0	$3.7	$1.6

Table 3-26. Additional Fuel Tank Storage Costs

Speed	**Medium**	**Medium**	**Medium**	**Low**	**Low**	**Low**
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Propulsion						
BSFC (g/kWh)	210	210	210	195	195	195
Load factor	73%	73%	73%	73%	73%	73%
Auxiliary						
Power (kW)	1,022	2,158	4,090	1,931	3,408	10,906
BSFC (g/kWh)	227	227	227	227	227	227
Load factor	31%	31%	31%	31%	31%	31%
Combined						
Fuel Amount (kg)	190,001	401,114	760,006	335,666	592,352	1,895,528
Density (kg/m^3)	960	960	960	960	960	960
Tank Size (m^3)	238	501	950	350	617	1,975
Tank Material (m^3)	0.46	0.75	1.15	0.59	0.87	1.88
Tank Material Cost ($)	$2,476	$4,072	$6,232	$3,203	$4,675	$10,145
Assembly						
Labor (hours)	5	6	7	10	12	15
Cost ($23.85/hr)	$119	$143	$167	$238	$286	$358
Overhead@40%	$48	$57	$67	$95	$114	$143
Total Assembly Cost	$167	$200	$234	$334	$401	$501
Total Variable Cost	$2,642	$4,272	$6,466	$3,537	$5,076	$10,646
Markup @ 29%	$766	$1,239	$1,875	$1,026	$1,472	$3,087
Total Hardware RPE	$3,409	$5,511	$8,341	$4,562	$6,548	$13,733

Case 2 is for retrofitting ships with equipment to allow fuel switching. It is similar to Case 1 costs, however, additional labor is allocated to installing the systems on a ship and additional R&D is provided to test systems on existing ships. Case 2 costs are given in Table 3-27.

Table 3-27. Case 2 Fuel Switching Costs (Retrofits)

Speed	**Medium**	**Medium**	**Medium**	**Low**	**Low**	**Low**
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Hardware Cost to Supplier						
Component Costs						
Additional Tanks	$3,409	$5,511	$8,341	$4,562	$6,548	$13,733
LFO Separator	$2,800	$3,300	$3,800	$3,800	$4,200	$4,700
HFO/LFO Blending Unit	$4,200	$4,700	$5,600	$4,700	$5,600	$6,600
3-Way Valve	$950	$1,400	$1,900	$1,400	$1,900	$2,800
LFO Cooler	$2,400	$2,800	$3,300	$2,800	$3,800	$4,700
Filters	$950	$950	$950	$950	$950	$950
Viscosity Meter	$1,400	$1,400	$1,400	$1,400	$1,400	$1,400
Piping/Pumps	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000
Total Component Cost	**$18,109**	**$22,061**	**$27,291**	**$21,612**	**$26,398**	**$36,883**
Assembly						
Labor (hours)	480	640	960	640	960	1200
Cost ($23.85/hr)	$11,446	$15,262	$22,892	$15,262	$22,892	$28,615
Overhead @ 40%	$4,578	$6,105	$9,157	$6,105	$9,157	$11,446
Total Assembly Cost	**$16,025**	**$21,366**	**$32,049**	**$21,366**	**$32,049**	**$40,062**
Total Variable Cost	$34,133	$43,427	$59,340	$42,979	$58,447	$76,945
Markup @ 29%	$9,899	$12,594	$17,209	$12,464	$16,950	$22,314
Total Hardware RPE	**$44,032**	**$56,021**	**$76,549**	**$55,442**	**$75,397**	**$99,259**
Fixed Costs						
R&D Costs (0.33 year R&D)	$227,040	$227,040	$227,040	$227,040	$227,040	$227,040
Marine Society Approval	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000
Engines/yr.	40	40	40	40	40	40
Years to recover	5	5	5	5	5	5
Fixed cost/engine	**$1,618**	**$1,618**	**$1,618**	**$1,618**	**$1,618**	**$1,618**
Total Costs	**$45,265**	**$57,254**	**$77,782**	**$56,675**	**$76,630**	**$100,492**
Cost per kW	$10.1	$6.0	$4.3	$6.7	$5.1	$2.1

3.6. Differential Fuel Consumption

Fuel consumption increases/decreases were calculated for a 1 percent change in BSFC. The values shown in Table 3-28 can be scaled up or down relative to the amount of fuel consumption benefit or penalty.

Table 3-28. Hourly fuel use change estimated for a one percent change in brake specific fuel consumption

Speed	**Medium**	**Medium**	**Medium**	**Low**	**Low**	**Low**
Engine Power (kW)	**4,500**	**9,500**	**18,000**	**8,500**	**15,000**	**48,000**
Cylinders	**9**	**12**	**16**	**6**	**8**	**12**
Liters/cylinder	**35**	**65**	**95**	**380**	**650**	**1400**
Engine Speed (rpm)	**650**	**550**	**500**	**130**	**110**	**100**
Load Factors, % of hp	73%	73%	73%	73%	73%	73%
Avg BSFC, g/kWh	210	210	210	195	195	195
HFO Fuel Usage Tonnes per hour	0.69	1.45	2.75	1.21	2.13	6.82

3.7. IMO Testing Costs

IMO testing is done on a representative engine for an engine family. This engine represents the worst case specification (i.e., the highest NOx emissions). It is emission tested on a test bed before sending it to the customer. Other similar engines are referred to as an engine family and are not tested.

A technical file is submitted with the engine. It would contain the identification of the components, settings and operating values of the engine that influence NOx emissions. The critical components are marked with IMO-ID numbers and relevant parameters are identified, providing an easy means of compliance checking onboard the ship. Identification of the full range of allowable adjustments or alternatives for the components of the engine are also listed along with a system of onboard NOx verification procedures (component and setting checks) to verify compliance with the IMO NOx emission limits during onboard verification surveys.

The cost of Marine Society approval is estimated at $5,000.

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