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# Incremental Cost Estimates for Marine Diesel Engine Technology Improvements

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Engine Programs and Compliance Division
Office of Mobile Sources
U.S. Environmental Protection Agency

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**MEMO** **EPA420-R-98-021**

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TRANSPORTATION
TECHNOLOGY

From:
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Date:
30 September 1998

Subject:
Incremental Cost Estimates for Marine Diesel Engine Technology Improvements

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## INTRODUCTION

The United States Environmental Protection Agency (EPA) plans to propose emission standards for new propulsion and auxiliary marine compression ignition engines rated at or above 50 horsepower (37 kW). This memorandum provides incremental cost analyses for some of the technologies most likely to be used to meet the new emission standards. Most marine engines of less than 6,000 horsepower (5,000 kW) are expected to be derived from land-based engines. Emission standards for on-highway, for nonroad, and for locomotive diesel engines have already been adopted by EPA. Because these standards are already in place, the technology exists for land-based engines to meet emission standards. Marine engines will be expected to meet similar standards, thus this report details the costs to convert a land-based nonroad engines meeting the appropriate, land-based emission standards into an engine suitable for marine use and meeting marine emission standards. The technologies from this conversion process that are considered in this report are for improvements related to turbocharging and aftercooling, which are specific to the marine engine and distinct from those required for the equivalent engine's land-based application. Consideration is also given to the additional development time required for adopting land-based engine technologies, such as optimizing calibrations and reprogramming electronic controls. The appendix at the end of this document includes tables that summarize these marine-specific costs.

To estimate the costs of these marine engine technologies, five 'test case engines' were used with each test case representing a power range with similar characteristics. Table 1 describes the power ranges used to calculate separate costs and the nominal power values that define the test case engines representing the various power ranges.

Table 1. Power Ranges and Nominal Power for Estimating Costs

| **Engine Power Ranges** | | **Nominal Engine Power** | |
|---|---|---|---|
| **HP** | **kW** | **HP** | **kW** |
| 50-300 | 37-225 | 130 | 100 |
| 300-750 | 225-560 | 500 | 400 |
| 750-1500 | 560-1000 | 1000 | 750 |
| 1500-2500 | 1000-2000 | 2000 | 1500 |
| 2500-6000 | 2000-5000 | 4000 | 3000 |

This report considers three aspiration and cooling circuit configurations for each nominal engine horsepower. Case 1 is a naturally-aspirated diesel marine engine using coolant fluid circulated through a heat exchanger to cool the engine. Case 2 is a turbocharged and aftercooled version of Case 1 engine. These technologies are cooled by the same volume of coolant fluid that is circulated through the engine and a common heat exchanger. Engines that are currently on the market and are not naturally-aspirated have some kind of turbocharging, with or without aftercooling. There is a great deal of variability in the power and sophistication of turbochargers in use today.

Case 3 is similar to Case 2, however the aftercooler in Case 3 is cooled separately from the engine (separate-circuit aftercooling). In this configuration, the aftercooler is cooled by a volume of coolant water or directly by seawater and is in a separate cooling circuit from the engine. For calculating incremental costs, Case 1 serves as the baseline configuration; each component expected to change in Case 2 or Case 3 is described in the following pages.

## BACKGROUND

Diesel engines used in marine applications span a wide range of technologies and applications from small auxiliary engines to very large ocean-going propulsion engines. In broad terms, a marine engine can be treated as belonging to one of three categories: those that are derived from or use primarily land-based nonroad technologies; those that are derived from or use primarily locomotive technologies; and those that are manufactured on a unique basis or in small groups for propulsion of very large ocean-going vessels. EPA has recently set emission limits for nonroad engines and for locomotive engines.

Through combinations of combustion chamber improvements, fuel injection improvements, advances in low temperature charge air cooling, and exhaust gas recirculation, manufacturers are designing these power systems to meet applicable emissions standards. It is therefore expected that marine engines using nonroad and locomotive based engines will already incorporate many of these improved technologies. This report examines the costs to upgrade these engines with new or improved turbocharging and aftercooling to meet new emission limits for marine engines. While land-based engines also use these technologies, marine applications call for unique designs.

Two major classifications of CI engines are discussed here. The first is natural aspiration, in which air is drawn into the cylinder by the vacuum created from the piston's downstroke. The second classification uses a turbocharger to compress the charge air before it enters the cylinder. By compressing the air charge, more air mass is available in the cylinder for combustion, allowing more fuel to be injected and creating more power per stroke for the engine. Turbocharging increases the power-to-weight ratio of the engine, reduces PM formation, and enables aftercooling of the charge air, but leads to increased combustion temperatures and greater pressures in the cylinder over those found in a naturally-aspirated engine. Few of the smallest CI marine engines are turbocharged, but most engines greater than 300 horsepower have some kind of turbocharging.

An aftercooler is often used between the turbocharger and the engine to cool the charge air. This cooling makes the air denser and allows more air to enter the cylinder. By lowering the charge air temperature, the peak combustion temperature is also reduced, thereby reducing NOx emissions. The increased charge air density also increases power density, allowing a smaller displacement engine to do the work that would normally require a larger engine. Another benefit of aftercooling is the potential to improve brake-specific fuel consumption (BSFC). Studies by Ricardo's Information Research Service show an average of a 3% improvement in BSFC for a turbocharged engine over natural aspiration and 6% improvement for turbocharged and aftercooled over natural aspiration at the same brake specific NOx levels. Many factors affect to BSFC including engine design, load factors that depend on engine use characteristics, and add-on technologies implemented by the boat-builder or vessel operator. Actual BSFC improvements for a separate-circuit configuration would therefore be hard to predict and would be dependent on NOx emission levels, but even a small improvement in BSFC shows significant cost savings in fuel over the life of the engine. Estimated fuel savings are presented below.

Reducing the temperature of the charge air can be achieved several ways. The most common charge air coolers in marine applications are water-to-air aftercoolers. This type of aftercooler is equivalent to the jacket-water aftercoolers commonly used for land-based applications, except that the jacket-water which cools the marine aftercooler is cooled by seawater whereas the jacket-water to cool a land-based aftercooler is cooled by ambient air. Due to their operating environment, marine engines typically have a virtually unlimited supply of cool water for onboard cooling. The limited space in marine engine compartments and the fact that engine rooms are often located deep within the vessel dictates that engine heat be discharged to seawater rather than to ambient air. Several configurations relating the engine, turbocharger, aftercooler, and heat exchanger are possible. Three different configurations are explained and analyzed for relative costs below.

**Case 1: Engine with Onboard Heat Exchanger**

The first case is the simplest case - a naturally-aspirated engine and onboard heat exchanger. There is no turbocharger and no aftercooler associated with this configuration. Seawater is strained and brought into the heat exchanger to cool the jacket-water. The jacket-water passes from the heat exchanger to the engine and back thereby cooling the engine. This configuration is generally found on older propulsion engines and most auxiliary engines rated under 100 horsepower. Although combustion chamber design and the fuel delivery system can be optimized to increase power and reduce emissions, it is generally expected that naturally-aspirated engines will have a difficult time meeting the new, proposed emission standards.

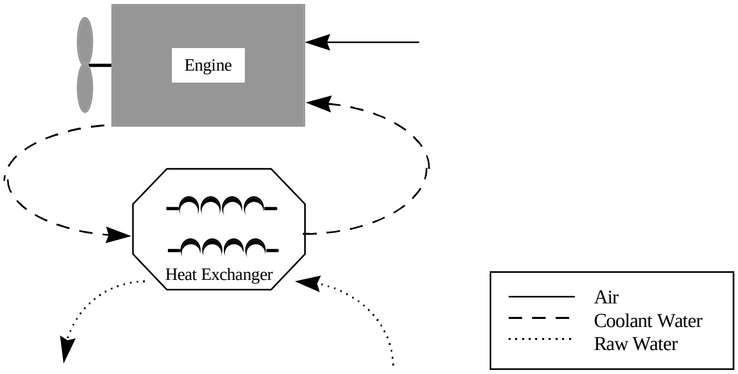

Figure 1: Example of a naturally-aspirated engine with a heat exchanger (or keel cooler) (Case 1)

**Case 2: Turbocharger and Aftercooler in the Engine Coolant Loop**

The first aftercooler configuration is shown in Figure 2. This case is a turbocharged and aftercooled version of the Case 1 configuration. The aftercooler is integrated into the engine's coolant loop. Thus, the same coolant that cycles between the onboard heat exchanger or keel cooler and the engine is also circulated through the aftercooler, and the coolant that absorbs heat from the engine block also absorbs heat from the aftercooler. This approach is regularly used in CI marine propulsion engines and large auxiliary engines.

The main advantage of a Case 2 configuration is the increased power-to-weight ratio due to the advantages of turbocharging and aftercooling. Although specific values vary between model lines, there is also a decrease in BSFC and a decrease in NOx emissions over a Case 1 engine. Another advantage is that design, installation, operation, and maintenance of Case 2 systems is generally well established and well supported by the engine manufacturers, ship builders, and vessel operators.

The main drawback of conventional aftercooling is that the charge air temperature rarely drops below 180°F. The coolant water enters the onboard heat exchanger or keel cooler at roughly 180-200°F and drops 10 to 15°F. After compression in the turbocharger, the charge air is at 300 to 350°F. The engine coolant leaving the heat exchanger is at approximately 180°F, so the charge air temperature is typically lowered to 220 to 240°F. The cooler the charge air, the more dense it is and the more air can be drawn into the cylinder per stroke. More air at lower temperatures generally supports a larger power-to-weight ratio for the engine and reduced NOx emissions.

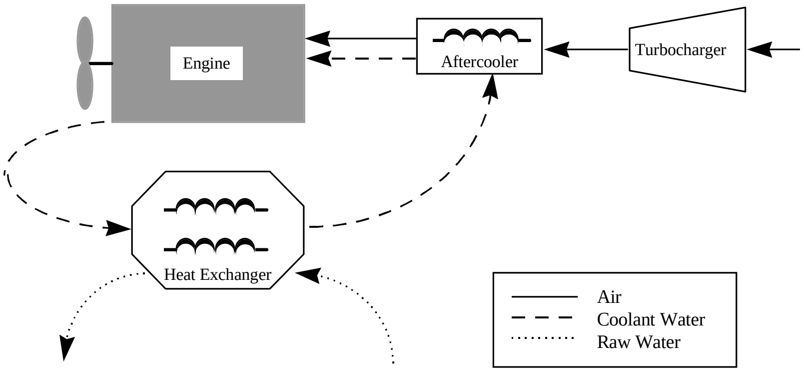

Figure 2: Example of a turbocharger and aftercooler in the same engine coolant loop (Case 2)

### Case 3: Separate-circuit Aftercooler

A cooling technology that takes advantage of the vast resource of cool water available to marine engines is a separate-circuit aftercooler. In this configuration, a completely separate coolant loop is formed that consists of the aftercooler, a small heat exchanger, a coolant pump, and associated plumbing. The conventional cooling circuit consisting of a larger heat exchanger, a coolant pump, and associated plumbing is very similar to that described for Case 2. Both circuits can use the same raw water pump; the raw water would then simply be split before the heat exchangers to send a fraction to the aftercooler's heat exchanger and the rest to the engine's heat exchanger. The concept of separate-circuit aftercooling is illustrated in Figure 3.

Separate-circuit aftercooling provides the same advantages as those described for jacket-water aftercooling (Case 2), but to a greater degree. Since the separate-circuit heat exchanger can cool the charge air to within 30°F of the seawater, charge air temperatures can be controlled to optimum levels.

The disadvantages of separate-circuit aftercooling are the additional costs of hardware and the additional complexity of two separate cooling systems. However, the anticipated improvements in BSFC are likely to lead to significant savings in the total life-cycle costs of the system. There is also some concern among engine manufacturers that lowering the charge air temperature below 130°F will lead to condensation in the charge air and the possibility of increased wear on the engine. More research may be necessary to address this concern and, if it is found to be valid, a thermostat with a proportioning bypass valve could be installed with the separate-circuit to control the flow of seawater and thereby control the temperature of the charge air.

A variation of separate-circuit aftercooling is commonly used for recreational CI marine engines. Commonly referred to as direct seawater aftercooling, this configuration involves routing seawater directly through the aftercooler. This achieves maximum cooling of the charge air and reduces cost by eliminating the intermediate heat exchanger but technical drawbacks prevent this from being used in commercial applications. The principal concern is for the increase in maintenance costs to address corrosion of the more extensive seawater plumbing and the potential for catastrophic failure if a pipe would fail in the engine or engine room. Because direct seawater aftercooling is not projected for commercial applications and is already widely used for recreational applications, no increased use of seawater aftercooling is anticipated to result from new emission standards. This report therefore does not include estimated costs for this technology.

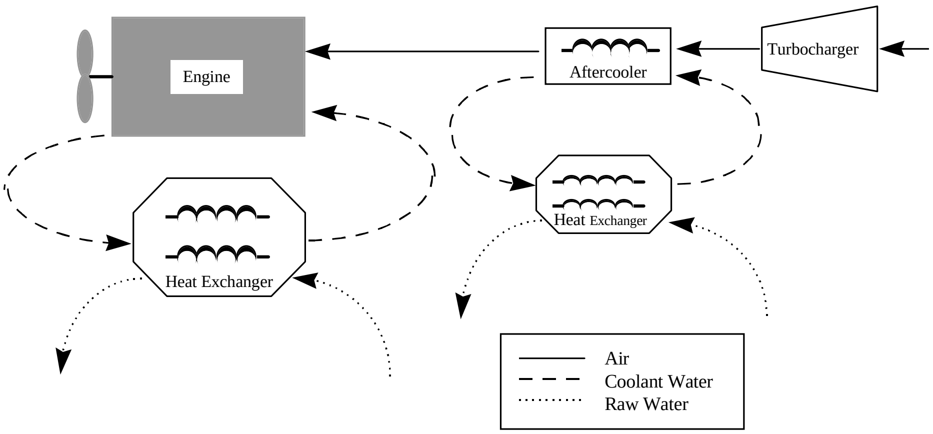

Figure 3: Example of a separate-circuit aftercooler (Case 3A)

A detailed description of the technology and hardware associated with these turbocharging and aftercooling configurations are presented below. The attached spreadsheets in Tables A-1 through A-5 in the appendix show the costs for engines ranging from 130 to 4,000 nominal horsepower (100 to 3,000 kW). The 130 and 500 horsepower (100 and 400 kW) engines are derived from technology used in land-based nonroad engines that in turn are derived from highway engine technology. The 1,000 and 2,000 horsepower (750 and 1,500 kW) engines are derived from land-based off-road engine technology. The 4,000 horsepower (3,000 kW) engine is derived from locomotive engine technology.

## COST METHODOLOGY

The costs for different aspiration and cooling technologies are presented to provide information on marine-specific incremental costs. Representative models were chosen from the test case power ranges studied for this report. No single model was used for developing all cost information in this report, but rather a composite engine with characteristics of all the representative models in the applicable power range was used. Engines were considered from Cummins, Caterpillar, Detroit Diesel, Electromotive Division of General Motors, Daytona, John Deere, and Warstila NSD. Models from these manufacturers were chosen to give structure to the data collection process and are not included for endorsement purposes.

Hardware costs depend on the individual engine model complexity and volume sold. Average engine or vessel parameters and configurations were used to develop the costs. For example, an engine with 16 or more cylinders will have multiple turbochargers and aftercoolers while a more compact engine of the same power output might only have one turbocharger and aftercooler. Another example is the cost of plumbing. A tugboat will have high-power engines in a very compact setting which requires minimal lengths of piping while a similar high-power engine used for auxiliary power on a large ocean-going vessel may be located several decks away from the heat exchanger cooling system thereby requiring a much larger amounts of piping. All costs are reported in 1997 dollars.

Assembler labor rates were obtained from U.S. Department of Labor (DOL) statistics for the Michigan and Midwest regions [1] and inflated to 1997 dollars using DOL labor cost indices [2]. Based on this information, labor rates used in this report are $17.50 per hour plus a 60 percent fringe rate providing a cost of direct labor of $28 per hour.

In most cases, estimated component costs were based on either the discounted retail price of replacement parts or were built up from models developed by ARCADIS Geraghty & Miller. Much of the hardware and cost information was gathered from engine manufacturers, component manufacturers, and shipbuilders. Where discounted prices of replacement parts were used, estimates of supplier component prices were determined from retail prices for replacement parts. These prices were discounted to 33 percent of the retail price for use in the equations for calculating the retail price equivalent. Lindgren [3] discounted retail prices to 20 or 25 percent for use in his calculations. Although the low sales volumes and the specialty nature of many technologies in the marine industry may lead to higher markups, it is the belief of the authors that 33 percent is more realistic in today’s competitive retail market. If a different markup can be quantified, the cost estimates in Tables 2 through 6 should be adjusted accordingly.

Discounted retail prices already include the costs of the supplier raw materials, supplier labor and labor overhead, and a reasonable markup for the supplier. Labor overhead in these analyses is assumed to be 40 percent of the cost of direct labor as cited in Lindgren [3]. Manufacturer overhead and manufacturer profit, when added together, are assumed to be 29 percent as cited by Jack Faucett Associates [4]. The general formula used to determine the component cost to the manufacturer is:

$$\text{Component Cost} = \{M + L * 1.4\} * 1.29$$

where:

M = Total Hardware Cost to the Manufacturer (materials) and

L = Labor (to install the components on the engine and on the vessel)

Fixed costs will include extensive efforts to test and map engine performance in the new marine configuration. Fixed costs included in this report are those that are incremental to the costs that a Case 1 engine would require. These costs reflect efforts to maximize aftercooler and turbocharger effects on the engine performance and the additional testing required to develop performance characteristics for the separate-circuit aftercooler technology which requires a greater degree of development.

The estimates presented in this report represent costs in the first year of production of components on a nationwide scale. Production costs related to direct and indirect labor are likely to fall in subsequent years as workers gain skill, develop shortcuts, and improve the flow of tasks. Costs for materials are also likely to decline over time, although not as rapidly as labor costs due to methods for reducing waste or using lower cost materials.

## TECHNOLOGY

**Turbocharger**: Turbochargers used on marine engines must operate with reduced surface temperatures and are therefore typically cooled using engine coolant, which substantially increases their cost. The sophistication and performance of turbochargers for marine engines varies widely which makes it difficult to precisely estimate turbocharger costs over a wide range of engine models. Turbocharger costs were estimated based on a quote from a turbocharger manufacturer that turbochargers for engines in the horsepower ranges 400 to 2,000 horsepower (300 to 1,500 kW) are sold for $1.50 per engine horsepower in bulk shipments of greater than 1,000 pieces to the original engine manufacturer (OEM). The factor used in the calculations was $1.60 per turbocharger to account for some smaller volume sales or slightly more sophisticated technologies.

Dual turbochargers and even quadruple turbochargers are used in some applications, usually for engines with 12 or more cylinders. Some locomotive-sized engines have 16 or 20 cylinders and therefore use four turbocharger/aftercooler combinations, one for each set of 4 or 5 cylinders. This reduces pumping losses and reduces the overall equipment size. In this report, the engines rated at 2,000 horsepower (1,500 kW) were treated as having dual turbochargers of total cost of $1.90 per engine horsepower. The 4,000 horsepower (3,000 kW) engines were costed to have four turbochargers, each one servicing one quarter of the total engine horsepower at $1.90 per horsepower. Information from some manufacturers suggests that turbochargers for large medium-speed engines will be significantly more expensive, ranging from $25,000 to $100,000 apiece for rebuilt and new turbochargers, respectively. If a discount factor of one third is applied to these prices to account for engine and equipment supplier markups, supplier costs range from approximately $8,300 to $33,000, which falls within the range of the costs used in this report.

**Cooling System**: The total cooling system cost is the sum of the aftercooler, heat exchanger, raw water pump, plumbing, coolant, coolant pump, thermostat and wiring costs, as estimated below.

*Aftercooler:* Aftercooler costs were estimated from supplier price estimates and from aftermarket prices from parts suppliers discounted to one third of retail price. The factor used to determine nominal aftercooler cost in the calculations was $1.35 per engine horsepower. Aftercooler costs for were increased by 10 percent over Case 2 to account for more durable materials and extra manufacturing costs that might be required to produce an aftercooler capable of withstanding larger temperature changes.

*Heat Exchanger*: Heat exchanger costs were estimated for units that used copper-nickel tube bundles and copper shells. Copper-nickel is often used with seawater as it is corrosion resistant and has a high heat transfer coefficient. As other corrosion resistant materials are also used to make heat exchangers, the prices in this report can be scaled using a ratio of the alternate metal’s cost to the cost for copper-nickel. Price estimates were based on engineering calculations conducted by ARCADIS Geraghty and Miller and verified by price estimates from independent heat exchanger manufacturers. The factor used here was $1.85 per engine horsepower for the heat exchanger used with the Case 1 engine. This cost was increased by 25% to $2.30 per engine horsepower for Case 2. The cost for a Case 2 heat exchanger was increased by 50% to $3.45 to account for the addition of a second heat exchanger of approximately half the size in Case 3.

A keel cooler could be used in place of a heat exchanger. A simple way to visualize a keel cooler is to picture a heat exchanger mounted on the hull of the vessel under the water line. Coolant fluid is piped to the keel cooler and raw water flows by on the outside of the unit. In this way, no raw water is brought into the vessel. If a vessel owner wants a keel cooler, it is usually designed as part of a new vessel as keel coolers are a difficult retrofit option. The keel cooler is slightly more expensive than a standard, OEM-supplied heat exchanger but requires less maintenance as there is no internal fouling of tube bundles, raw water pipes, or raw water pumps. The keel cooler is also safer since no seawater is pumped into the ship. However, a keel cooler may not be able to support the cooling needs of larger engines. The efficiency of a keel cooler is often less than that of a heat exchanger as the wall thickness of a keel cooler is greater that the tube thickness of a heat exchanger and thus has more resistance to heat transfer. The weight of a keel cooler is also a concern for some vessel operators.

*Raw Water/Seawater Pump*: When an internal heat exchanger is used, a pump is required to bring the seawater into the heat exchanger bundles. The rate of seawater flow is often similar for engines under 1,000 horsepower (750 kW). Pump costs are based on estimates from vendors who supply pumps to the OEM for installation on the engine. Raw water pumps are engine driven and do not require separate motors, controls, or additional wiring. Smaller horsepower engines with lower operating hours often use a rubber impeller pump with a bronze housing. Larger engines that require higher flowrates or engines that are operated for the long hours, typical of commercial applications, often use centrifugal pumps with bronze blades and housings.

The same price estimates were used for Case 1 and Case 2 raw water pumps. This is reasonable because the added heat load of the turbocharger and aftercooler is carried by increasing the flow rate (within the allowable boundaries of the existing pump) and upgrading the efficiency of the heat exchanger. For the upgrade to a separate-circuit aftercooler, the analysis assumes that the raw water pump will need to be upgraded to the next flow rate level. The addition of a separate-circuit aftercooler is expected to add 30 gpm to the Case 2 flow rate for engines under 1,000 horsepower (750 kW) and 60 gpm for engines greater than 2,000 horsepower (1,500 kW). The base price is $500 for a pump rated at 100 gpm plus an additional $100 for each additional 30 gpm.

*Coolant/Fresh Water Pump*: The coolant fluid pump is a centrifugal pump powered by the engine. No changes will need to be made to this pump between Cases 1 and 2. Case 3 requires the addition of a separate coolant pump. This pump will be a small fraction of the size and cost of the primary coolant pump. Pump prices are based on aftermarket parts suppliers, discounted to 1/3 of their listed price.

*Plumbing*: Plumbing consists of all the pipes and hoses used for the raw water circuit and the coolant water circuit. The raw water circuit brings seawater into the heat exchanger and returns it slightly warmer after it has circulated through the heat exchanger. The coolant loop carries coolant to the engine pump from the heat exchanger and then for the Case 2 configuration, carries part of the coolant to the aftercooler and part to the engine. The heated coolant then returns to the heat exchanger. Engines in the 130 and 500 nominal horsepower (100 and 400 kW) ranges are compact units with the aftercooler, turbocharger, and heat exchanger all mounted on or very close to the engine block. Thus, the lengths of coolant piping for these engines are small and not likely to add much cost to the overall system. For the 500 horsepower (400 kW) engine, a total of 10 feet of 2" OD steel pipe at $1.20 per foot was used for the coolant loop in Case 1, 10 feet in Case 2, and 20 feet in Case 3. The raw water circuit used a total of 20 feet in Case 1 and 20 feet in Case 2 of 2" copper-nickel pipe at $3.60 per foot. Case 3 used 40 feet of the same pipe to feed raw water to the two heat exchanger circuits. Larger engines (greater than 1,000 horsepower (750 kW)) will sometimes have auxiliary systems such as heat exchangers mounted in other compartments or even in other decks of the ship than the main propulsion engine(s). More extensive lengths of piping were costed for the larger engines (e.g. up to 160 feet of 4" copper tubing for a 4,000 horsepower (3,000 kW) engine).

*Coolant*: Ethylene glycol and water are mixed to create the coolant fluid. As more coolant will be needed for the separate-circuits of Case 3, coolant costs are included in the incremental cost estimates. The concentration of ethylene glycol in the coolant varies depending on the use of the vessel and the climate it most frequently operates in. For this study, mixed coolant was estimated at $0.50 per gallon with coolant tanks varying from 30 to 150 gallons.

*Thermostat*: Thermostat costs are expected to increase modestly or not at all between the various cases. While the algorithms governing thermostatic controls may change with the addition of turbochargers and aftercoolers to the engine, it is not expected that the actual thermostat hardware will change or that an additional thermostat will be required.

*Wiring*: Estimated wiring costs varied widely in our investigation. While one manufacturer stated that nearly $500 worth of wiring needed to be added on an aftercooled, turbocharged, and electronically controlled engine, other estimates were much lower. For these cost analyses, ARCADIS Geraghty and Miller treated the $500 cost as though it included both for the wire and the installation labor. Actual costs of wire in this report are $10 to $25 depending on the size of the engine with additional costs factored into the installation labor costs for each case.

## FIXED COSTS

Fixed costs are included to show the development costs incremental to the Case 1 baseline that will be required for Case 2 and Case 3 engines. These incremental costs are for such efforts as adjusting and fitting the water cooled manifold system, the water cooled turbocharger, and the aftercooler system to the engine as well as costs for lab tests and field tests of engine performance. Although Case 2 technologies already exist in land-based nonroad engines of equivalent power ratings, their transfer to marine applications will require additional development costs such as testing and setting the injection characteristics of the engine over those required for the land-based engine.

Fixed costs are calculated based on the development costs per model line obtained by conversations with several engine manufacturers. Fixed costs per model line range from $400,000 to $1.4

million depending on the degree of redesign and the size of the engine. Higher costs are expected for larger engines due to the additional expense of fabricating prototype parts and conducting engine tests. These development costs per model line are amortized over 5 years at seven percent interest per annum. Fixed costs per engine are found by taking the amortized development costs per model line, dividing by the engine sales per year, and multiplying by the model lines in the power range. Some manufacturers have indicated that there will be fewer model lines for engines meeting new emission standards. While a reduction in model lines has not been included in the fixed cost estimates of this report, streamlined production offerings would result in reduced fixed costs per engine.

## IMPROVEMENTS IN BRAKE SPECIFIC FUEL CONSUMPTION

As described earlier, turbocharging and aftercooling an engine improve the engine's BSFC. Lifetime fuel cost savings for each one percent improvement in BSFC are detailed in Table A-6 and summarized in Table 2. Baseline BSFC numbers were obtained from marketing information available from Cummins, EMD and DDC for engines in the test case engine horsepower ranges. Load factors, annual hours of operation, and engine lifetime were obtained from Power Systems Research and are expected to be representative for the test case engines. The average cost per gallon of API 35 fuel was based on EPA estimates of nationwide fuel prices at $0.65 per gallon. If fuel prices increase over time, the value of the BSFC improvement will increase correspondingly.

Table 2 - Lifetime Savings From One Percent Improvement in BSFC

| | **130 hp** | **500 hp** | **1,000 hp** | **2,000 hp** | **4,000 hp** |
|---|---:|---:|---:|---:|---:|
| **Commercial** | $781 | $3,626 | $7,857 | $20,049 | $46,257 |
| **Auxiliary** | $613 | $2,561 | $4,641 | $9,159 | $18,560 |

Annual fuel costs per engine were determined by multiplying the BSFC by the estimated annual operating hours, load factor, rated horsepower, and cost of fuel per gallon then dividing by fuel density. This annual cost was then extended over the expected lifetime of the engine and brought to the net present value of money using a seven percent interest discount rate.

## RESULTS

Table 3 presents the total and incremental costs associated with each of the nominal test case engines examined in this study. More detailed analysis is available in the Appendix.

Table 3 - Estimated System and Incremental Cost Estimates

| Engine Power Ranges (Hp) | Nominal Engine Power (Hp) | Case 1 | | Case 2 | | Case 3 | |
|---|---|---|---|---|---|---|---|
| | | System | Incremental | System | Incremental | System | Incremental |
| 50 - 300 | 130 | $2,582 | -- | $4,236 | $1,655 | $5,167 | $2,585 |
| 300 - 750 | 500 | $4,417 | -- | $9,954 | $5,536 | $12,493 | $8,075 |
| 750 - 1,500 | 1,000 | $8,688 | -- | $26,436 | $17,748 | $32,721 | $24,032 |
| 1,500 - 2,500 | 2,000 | $14,972 | -- | $41,391 | $26,419 | $50,943 | $35,971 |
| 2,500 - 6,000 | 4,000 | $25,058 | -- | $70,715 | $45,657 | $86,427 | $61,369 |

## REFERENCES

1. "Industry Wage Survey: Motor Vehicles and Parts 1989," U.S. Department of Labor, Bureau of Labor Statistics, October 1991, Bulletin 2384, page 7.

2. "Employment Cost Indexes and Levels, 1975-1994," U.S. Department of Labor, Bureau of Labor Statistics, September 1994, Bulletin 2447, page 65.

3. Lindgren, Leroy H., "Cost Estimations for Emission Control Related Components/Systems and Cost Methodology Description," Rath & Strong, Inc., Report No. EPA 460/3-78-002, December 1977.

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

# APPENDIX

Explanatory notes for Tables A-1 through A-5

- Case 1: Naturally-Aspirated Engine with Onboard Heat Exchanger
- Case 2: Engine with Turbocharger and Aftercooler in the Engine Coolant Loop
- Case 3: Separate Circuit Aftercooler
- Raw water pump may require an upgrade for Case 2 if flows need to increase appreciably due to aftercooler heat load. In most cases, it will be sufficient to increase the effectiveness of the heat exchanger.
- Development costs included above are for marine specific development. Costs for electronic controls and combustion optimization already included in the development of the equivalent industrial and locomotive engines.
- Engines per year for Case 2 and Case 3 are a sum of auxiliary and commercial sales as projected by PSR for the horsepower range.
- Number of Heat Exchangers Required - The line item price for Case 3 is the combined price for both units.

Table A-1: Incremental Costs for marine diesel engine technology improvements, 50 to 300 HP

| **Nominal Engine hp** | 130 | | # Cylinders | 4 |
|---|---|---|---|---|
| **Hardware Cost to Manufacturer** | | **Case 1** | **Case 2** | **Case 3** |
| Turbocharger (each) | | $0 | $208 | $208 |
| Number Required | | 0 | 1 | 1 |
| Aftercooler (each) | | $0 | $176 | $194 |
| Number Required | | 0 | 1 | 1 |
| Heat Exchanger (total) | | $227 | $284 | $426 |
| Number Req. (see explanatory note) | | 1 | 1 | 2 |
| Fresh Water Pump | | $91 | $91 | $137 |
| Raw Water Pump | | $225 | $225 | $325 |
| Piping Total | | $44 | $44 | $90 |
| Fresh water Pipe @ 2" | feet | 6 | 6 | 8 |
| | total fresh water pipe cost | $7 | $7 | $10 |
| Raw Water Pipe @ 2" | feet | 10 | 10 | 22 |
| | total raw water pipe cost | $36 | $36 | $80 |
| Coolant | | $8 | $8 | $13 |
| Thermostat | | $15 | $15 | $15 |
| Wiring | feet | 50 | 55 | 60 |
| | cost | $20 | $25 | $27 |
| **Total Hardware Cost** | | **$630** | **$1,075** | **$1,434** |
| | **Assembly** | | | |
| Labor @ $28/hr | hours | 35 | 40 | 46 |
| | total labor cost | $980 | $1,120 | $1,288 |
| Overhead @ 40% | | $392 | $448 | $515 |
| Total Assembly Cost | | $1,372 | $1,568 | $1,803 |
| Markup on Hardware and Assembly @ 29% | | $580 | $767 | $939 |
| **Total Component Costs** | | **$2,582** | **$3,410** | **$4,176** |
| | **Fixed Costs** | | | |
| Development Costs Per Model Line | | | $400,000 | $480,000 |
| Engine Sales Per Year | | | 3284 | 3284 |
| Model Lines in Horsepower Range | | | 26 | 26 |
| Years To Recover | | | 5 | 5 |
| **Fixed cost/engine** | | | $826 | $992 |
| **Total Costs/engine** | | **$2,582** | **$4,236** | **$5,167** |
| **Total Incremental Costs** | | **$0** | **$1,655** | **$2,585** |

Table A-2: Incremental Costs for marine diesel engine technology improvements, 300 to 750 HP

| **Nominal Engine hp** | 500 |  | # Cylinders | 6 |
|---|---|---|---|---|
| **Hardware Cost to Manufacturer** |  | **Case 1** | **Case 2** | **Case 3** |
| Turbocharger (each) |  | $0 | $800 | $800 |
| Number Required |  | 0 | 1 | 1 |
| Aftercooler (each) |  | $0 | $677 | $745 |
| Number Required |  | 0 | 1 | 1 |
| Heat Exchanger (total) |  | $874 | $1,092 | $1,638 |
| Number Req. (see explanatory note) |  | 1 | 1 | 2 |
| Fresh Water Pump |  | $137 | $137 | $227 |
| Raw Water Pump |  | $500 | $500 | $600 |
| Piping Total |  | $85 | $85 | $170 |
| Fresh water Pipe @ 2" | feet | 10 | 10 | 20 |
|  | total fresh water pipe cost | $12 | $12 | $24 |
| Raw Water Pipe @ 2" | feet | 20 | 20 | 40 |
|  | total raw water pipe cost | $73 | $73 | $146 |
| Coolant |  | $15 | $15 | $25 |
| Thermostat |  | $15 | $15 | $15 |
| Wiring | feet | 50 | 55 | 60 |
|  | cost | $35 | $38 | $40 |
| **Total Hardware Cost** |  | **$1,660** | **$3,359** | **$4,260** |
|  | **Assembly** |  |  |  |
| Labor @ $28/hr | hours | 45 | 50 | 65 |
|  | total labor cost | $1,260 | $1,400 | $1,820 |
| Overhead @ 40% |  | $504 | $560 | $728 |
| Total Assembly Cost |  | $1,764 | $1,960 | $2,548 |
| Markup on Hardware and Assembly @ 29% |  | $993 | $1,543 | $1,974 |
| **Total Component Costs** |  | **$4,417** | **$6,862** | **$8,782** |
|  | **Fixed Costs** |  |  |  |
| Development Costs Per Model Line |  |  | $550,000 | $660,000 |
| Engine Sales Per Year |  |  | 1579 | 1579 |
| Model Lines in Horsepower Range |  |  | 15 | 15 |
| Years To Recover |  |  | 2 | 2 |
| **Fixed cost/engine** |  |  | $3,092 | $3,711 |
| **Total Costs/engine** |  | **$4,417** | **$9,954** | **$12,493** |
| **Total Incremental Costs** |  | **$0** | **$5,536** | **$8,075** |

Table A-3: Incremental Costs for marine diesel engine technology improvements, 750 to 1,500 HP

| **Nominal Engine hp** | 1000 |  | # Cylinders | 8 |
|---|---|---|---|---|
| **Hardware Cost to Manufacturer** |  | **Case 1** | **Case 2** | **Case 3** |
| Turbocharger (each) |  | $0 | $1,600 | $1,600 |
| Number Required |  | 0 | 1 | 1 |
| Aftercooler (each) |  | $0 | $1,355 | $1,490 |
| Number Required |  | 0 | 1 | 1 |
| Heat Exchanger (total) |  | $1,747 | $2,184 | $3,276 |
| Number Req. (see explanatory note) |  | 1 | 1 | 2 |
| Fresh Water Pump |  | $232 | $232 | $369 |
| Raw Water Pump |  | $1,000 | $1,000 | $1,200 |
| Piping Total |  | $128 | $128 | $255 |
| Fresh water Pipe @ 2" | feet | 15 | 15 | 30 |
|  | total fresh water pipe cost | $18 | $18 | $36 |
| Raw Water Pipe @ 3" | feet | 30 | 30 | 60 |
|  | total raw water pipe cost | $109 | $109 | $219 |
| Coolant |  | $35 | $35 | $43 |
| Thermostat |  | $25 | $25 | $25 |
| Wiring | feet | 55 | 60 | 65 |
|  | cost | $40 | $42 | $44 |
| **Total Hardware Cost** |  | **$3,207** | **$6,601** | **$8,302** |
|  | **Assembly** |  |  |  |
| Labor @ $28/hr | hours | 90 | 100 | 130 |
|  | total labor cost | $2,520 | $2,800 | $3,640 |
| Overhead @ 40% |  | $1,008 | $1,120 | $1,456 |
| Total Assembly Cost |  | $3,528 | $3,920 | $5,096 |
| Markup on Hardware and Assembly @ 29% |  | $1,953 | $3,051 | $3,885 |
| **Total Component Costs** |  | **$8,688** | **$13,572** | **$17,284** |
|  | **Fixed Costs** |  |  |  |
| Development Costs Per Model Line |  |  | $700,000 | $840,000 |
| Engine Sales Per Year |  |  | 142 | 142 |
| Model Lines in Horsepower Range |  |  | 10 | 10 |
| Years To Recover |  |  | 5 | 5 |
| **Fixed cost/engine** |  |  | $12,864 | $15,437 |
| **Total Costs/engine** |  | **$8,688** | **$26,436** | **$32,721** |
| **Total Incremental Costs** |  | **$0** | **$17,748** | **$24,032** |

Table A-4: Incremental Costs for marine diesel engine technology improvements, 1,500 to 2,500 HP

| **Nominal Engine hp** | 2000 |  | # Cylinders | 16 |
|---|---|---|---|---|
| **Hardware Cost to Manufacturer** |  | **Case 1** | **Case 2** | **Case 3** |
| Turbocharger (each) |  | $0 | $1,778 | $1,778 |
| Number Required |  | 0 | 2 | 2 |
| Aftercooler (each) |  | $0 | $1,505 | $1,656 |
| Number Required |  | 0 | 2 | 2 |
| Heat Exchanger (total) |  | $3,495 | $4,368 | $6,552 |
| Number Req. (see explanatory note) |  | 1 | 1 | 2 |
| Fresh Water Pump |  | $395 | $395 | $532 |
| Raw Water Pump |  | $2,000 | $2,000 | $2,200 |
| Piping Total |  | $310 | $310 | $620 |
| Fresh water Pipe @ 3" | feet | 45 | 45 | 90 |
|  | total fresh water pipe cost | $55 | $55 | $109 |
| Raw Water Pipe @ 3" | feet | 70 | 70 | 140 |
|  | total raw water pipe cost | $255 | $255 | $510 |
| Coolant |  | $45 | $45 | $60 |
| Thermostat |  | $25 | $25 | $25 |
| Wiring | feet | 65 | 70 | 75 |
|  | cost | $45 | $48 | $52 |
| **Total Hardware Cost** |  | **$6,314** | **$13,757** | **$16,908** |
|  | **Assembly** |  |  |  |
| Labor @ $28/hr | hours | 135 | 150 | 195 |
|  | total labor cost | $3,780 | $4,200 | $5,460 |
| Overhead @ 40% |  | $1,512 | $1,680 | $2,184 |
| Total Assembly Cost |  | $5,292 | $5,880 | $7,644 |
| Markup on Hardware and Assembly @ 29% |  | $3,366 | $5,695 | $7,120 |
| **Total Component Costs** |  | **$14,972** | **$25,332** | **$31,672** |
|  | **Fixed Costs** |  |  |  |
| Development Costs Per Model Line |  |  | $1,000,000 | $1,200,000 |
| Engine Sales Per Year |  |  | 130 | 130 |
| Model Lines in Horsepower Range |  |  | 8 | 8 |
| Years To Recover |  |  | 5 | 5 |
| **Fixed cost/engine** |  |  | $16,059 | $19,271 |
| **Total Costs/engine** |  | **$14,972** | **$41,391** | **$50,943** |
| **Total Incremental Costs** |  | **$0** | **$26,419** | **$35,971** |

Table A-5: Incremental Costs for marine diesel engine technology improvements, 2,500 to 6,000 HP

| **Nominal Engine hp** | 4000 | | # Cylinders | 20 |
|---|---|---|---|---|
| **Hardware Cost to Manufacturer** | | **Case 1** | **Case 2** | **Case 3** |
| Turbocharger (each) | | $0 | $2,133 | $2,133 |
| Number Required | | 0 | 4 | 4 |
| Aftercooler (each) | | $0 | $1,594 | $1,753 |
| Number Required | | 0 | 4 | 4 |
| Heat Exchanger (total) | | $6,989 | $8,737 | $13,105 |
| Number Req. (see explanatory note) | | 1 | 1 | 2 |
| Fresh Water Pump | | $671 | $671 | $871 |
| Raw Water Pump | | $2,800 | $2,800 | $3,200 |
| Piping Total | | $401 | $401 | $729 |
| Fresh water Pipe @ 3" | feet | 60 | 60 | 120 |
| | total fresh water pipe cost | $73 | $73 | $146 |
| Raw Water Pipe @ 4" | feet | 90 | 90 | 160 |
| | total raw water pipe cost | $328 | $328 | $583 |
| Coolant | | $75 | $75 | $100 |
| Thermostat | | $500 | $500 | $500 |
| Wiring | feet | 75 | 85 | 95 |
| | cost | $50 | $55 | $60 |
| **Total Hardware Cost** | | **$11,487** | **$28,148** | **$34,112** |
| Assembly | | | | |
| Labor @ $28/hr | hours | 203 | 225 | 293 |
| | total labor cost | $5,670 | $6,300 | $8,190 |
| Overhead @ 40% | | $2,268 | $2,520 | $3,276 |
| Total Assembly Cost | | $7,938 | $8,820 | $11,466 |
| Markup on Hardware and Assembly @ 29% | | $5,633 | $10,721 | $13,218 |
| **Total Component Costs** | | **$25,058** | **$47,689** | **$58,796** |
| | **Fixed Costs** | | | |
| Development Costs Per Model Line | | | $1,200,000 | $1,440,000 |
| Engine Sales Per Year | | | 68 | 68 |
| Model Lines in Horsepower Range | | | 5 | 5 |
| Years To Recover | | | 5 | 5 |
| **Fixed cost/engine** | | | $23,026 | $27,631 |
| **Total Costs/engine** | | **$25,058** | **$70,715** | **$86,427** |
| **Total Incremental Costs** | | **$0** | **$45,657** | **$61,369** |

## Table A-6: Lifetime fuel savings estimated for a one percent improvement in brake specific fuel consumption

| Load Factors, % of hp | 150 | 400 | 750 | 2000 | 5000 |
|---|---|---|---|---|---|
| Recreational | 30% | 30% | 40% | -- | -- |
| Commercial | 69% | 71% | 73% | 79% | 81% |
| Auxillary | 65% | 65% | 65% | 65% | 65% |
| | | | | | |
| **Annual Operating Hours, hr/yr** | **150** | **400** | **750** | **2000** | **5000** |
| Recreational | 225 | 225 | 500 | -- | -- |
| Commercial | 3000 | 3241 | 3769 | 4503 | 5000 |
| Auxillary | 2500 | 2500 | 2500 | 2500 | 2500 |
| | | | | | |
| **Lifetime, yr** | **150** | **400** | **750** | **2000** | **5000** |
| Recreational | 13 | 13 | 13 | -- | -- |
| Commercial | 15 | 15 | 15 | 15 | 15 |
| Auxillary | 17 | 17 | 17 | 17 | 17 |
| | | | | | |
| **Avg BSFC, lb/hp-hr** | **130** | **500** | **1000** | **2000** | **4000** |
| Commercial | 0.343 | 0.373 | 0.338 | 0.333 | 0.338 |
| 1% Improvement | 0.340 | 0.369 | 0.334 | 0.330 | 0.334 |

Avg Fuel Cost
Cost 35 API $ 0.65/gallon

Density 7.001 lb/gal

Fuel Savings with PV of money

| | | | 130 hp | 500 hp | 1000 hp | 2000 hp | 4000 hp |
|---|---|---|---|---|---|---|---|
| **Commercial** | Pre | | $8,576 | $39,814 | $86,270 | $220,132 | $507,875 |
| | | 1% | $8,491 | $39,415 | $85,407 | $217,930 | $502,796 |
| Present Value | Pre | | $78,114 | $362,619 | $785,737 | $2,004,940 | $4,625,678 |
| | | 1% | $77,333 | $358,993 | $777,879 | $1,984,891 | $4,579,421 |
| Savings | $/lifetime | | $781 | $3,626 | $7,857 | $20,049 | $46,257 |
| | | | | | | | |
| **Recreational** | Pre | | $285 | $1,191 | $6,396 | | |
| | 1% | | $282 | $1,179 | $6,332 | | |
| Present Value | Pre | | $2,598 | $10,850 | $58,258 | $0 | $0 |
| | | 1% | $2,572 | $10,741 | $57,676 | $0 | $0 |
| Savings | $/lifetime | | $26 | $108 | $583 | $0 | $0 |
| | | | | | | | |
| **Auxillary** | Pre | | $6,733 | $28,116 | $50,952 | $100,556 | $203,777 |
| | | 1% | $6,665 | $27,834 | $50,443 | $99,550 | $201,739 |
| Present Value | Pre | | $61,321 | $256,075 | $464,068 | $915,853 | $1,855,982 |
| | | 1% | $60,708 | $253,514 | $459,427 | $906,694 | $1,837,422 |
| Savings | $/lifetime | | $613 | $2,561 | $4,641 | $9,159 | $18,560 |

**Summary**

| | | | | | | |
|---|---|---|---|---|---|---|
| **Recreational** | $/lifetime | $ 26 | $ 108 | $ 583 | $ - | $ - |
| **Commercial** | $/lifetime | $ 781 | $ 3,626 | $ 7,857 | $ 20,049 | $ 46,257 |
| **Auxillary** | $/lifetime | $ 613 | $ 2,561 | $ 4,641 | $ 9,159 | $ 18,560 |

Sample Calculation:

Annual Payment = (Avg BSFC) * (Nominal hp) * (Load Factor) * (Annual hr of operation) / (Density) * (Cost 35 API)

Savings = (Pre Present Value) - (1% Present Value)

Table A-7: Heat Rejection

| | Engine Horespower | | | | |
|---|---|---|---|---|---|
| **Heat Rejected** | **130** | **500** | **1000** | **2000** | **4000** |
| Case 1: engine only (kW) | 98 | 375 | 740 | 1200 | 2200 |
| Case 2: engine & aftercooler -conventional (kW) | 228 | 505 | 955 | 1535 | 2585 |
| Case 3: engine & aftercooler - separate circuit (kW) | 253 | 530 | 995 | 1600 | 2655 |
| Increase (%), Case 1 to Case 2 | 133% | 35% | 29% | 28% | 18% |
| Increase (%), Case 2 to Case 3 | 11% | 5% | 4% | 4% | 3% |

**MEMO** **EPA420-R-98-021**

To:
Alan Stout - EPA, Office of Mobile Sources

Copies:
Jean Hoff - ICF

TRANSPORTATION
TECHNOLOGY

From:
Kassandra Genovesi and Louis Browning

Date:
30 September 1998

Subject:
Incremental Cost Estimates for Marine Diesel Engine Technology Improvements

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## INTRODUCTION

The United States Environmental Protection Agency (EPA) plans to propose emission standards for new propulsion and auxiliary marine compression ignition engines rated at or above 50 horsepower (37 kW). This memorandum provides incremental cost analyses for some of the technologies most likely to be used to meet the new emission standards. Most marine engines of less than 6,000 horsepower (5,000 kW) are expected to be derived from land-based engines. Emission standards for on-highway, for nonroad, and for locomotive diesel engines have already been adopted by EPA. Because these standards are already in place, the technology exists for land-based engines to meet emission standards. Marine engines will be expected to meet similar standards, thus this report details the costs to convert a land-based nonroad engines meeting the appropriate, land-based emission standards into an engine suitable for marine use and meeting marine emission standards. The technologies from this conversion process that are considered in this report are for improvements related to turbocharging and aftercooling, which are specific to the marine engine and distinct from those required for the equivalent engine's land-based application. Consideration is also given to the additional development time required for adopting land-based engine technologies, such as optimizing calibrations and reprogramming electronic controls. The appendix at the end of this document includes tables that summarize these marine-specific costs.

To estimate the costs of these marine engine technologies, five 'test case engines' were used with each test case representing a power range with similar characteristics. Table 1 describes the power ranges used to calculate separate costs and the nominal power values that define the test case engines representing the various power ranges.

Table 1. Power Ranges and Nominal Power for Estimating Costs

| **Engine Power Ranges** | | **Nominal Engine Power** | |
|---|---|---|---|
| **HP** | **kW** | **HP** | **kW** |
| 50-300 | 37-225 | 130 | 100 |
| 300-750 | 225-560 | 500 | 400 |
| 750-1500 | 560-1000 | 1000 | 750 |
| 1500-2500 | 1000-2000 | 2000 | 1500 |
| 2500-6000 | 2000-5000 | 4000 | 3000 |

This report considers three aspiration and cooling circuit configurations for each nominal engine horsepower. Case 1 is a naturally-aspirated diesel marine engine using coolant fluid circulated through a heat exchanger to cool the engine. Case 2 is a turbocharged and aftercooled version of Case 1 engine. These technologies are cooled by the same volume of coolant fluid that is circulated through the engine and a common heat exchanger. Engines that are currently on the market and are not naturally-aspirated have some kind of turbocharging, with or without aftercooling. There is a great deal of variability in the power and sophistication of turbochargers in use today.

Case 3 is similar to Case 2, however the aftercooler in Case 3 is cooled separately from the engine (separate-circuit aftercooling). In this configuration, the aftercooler is cooled by a volume of coolant water or directly by seawater and is in a separate cooling circuit from the engine. For calculating incremental costs, Case 1 serves as the baseline configuration; each component expected to change in Case 2 or Case 3 is described in the following pages.

## BACKGROUND

Diesel engines used in marine applications span a wide range of technologies and applications from small auxiliary engines to very large ocean-going propulsion engines. In broad terms, a marine engine can be treated as belonging to one of three categories: those that are derived from or use primarily land-based nonroad technologies; those that are derived from or use primarily locomotive technologies; and those that are manufactured on a unique basis or in small groups for propulsion of very large ocean-going vessels. EPA has recently set emission limits for nonroad engines and for locomotive engines.

Through combinations of combustion chamber improvements, fuel injection improvements, advances in low temperature charge air cooling, and exhaust gas recirculation, manufacturers are designing these power systems to meet applicable emissions standards. It is therefore expected that marine engines using nonroad and locomotive based engines will already incorporate many of these improved technologies. This report examines the costs to upgrade these engines with new or improved turbocharging and aftercooling to meet new emission limits for marine engines. While land-based engines also use these technologies, marine applications call for unique designs.

Two major classifications of CI engines are discussed here. The first is natural aspiration, in which air is drawn into the cylinder by the vacuum created from the piston's downstroke. The second classification uses a turbocharger to compress the charge air before it enters the cylinder. By compressing the air charge, more air mass is available in the cylinder for combustion, allowing more fuel to be injected and creating more power per stroke for the engine. Turbocharging increases the power-to-weight ratio of the engine, reduces PM formation, and enables aftercooling of the charge air, but leads to increased combustion temperatures and greater pressures in the cylinder over those found in a naturally-aspirated engine. Few of the smallest CI marine engines are turbocharged, but most engines greater than 300 horsepower have some kind of turbocharging.

An aftercooler is often used between the turbocharger and the engine to cool the charge air. This cooling makes the air denser and allows more air to enter the cylinder. By lowering the charge air temperature, the peak combustion temperature is also reduced, thereby reducing NOx emissions. The increased charge air density also increases power density, allowing a smaller displacement engine to do the work that would normally require a larger engine. Another benefit of aftercooling is the potential to improve brake-specific fuel consumption (BSFC). Studies by Ricardo's Information Research Service show an average of a 3% improvement in BSFC for a turbocharged engine over natural aspiration and 6% improvement for turbocharged and aftercooled over natural aspiration at the same brake specific NOx levels. Many factors affect to BSFC including engine design, load factors that depend on engine use characteristics, and add-on technologies implemented by the boat-builder or vessel operator. Actual BSFC improvements for a separate-circuit configuration would therefore be hard to predict and would be dependent on NOx emission levels, but even a small improvement in BSFC shows significant cost savings in fuel over the life of the engine. Estimated fuel savings are presented below.

Reducing the temperature of the charge air can be achieved several ways. The most common charge air coolers in marine applications are water-to-air aftercoolers. This type of aftercooler is equivalent to the jacket-water aftercoolers commonly used for land-based applications, except that the jacket-water which cools the marine aftercooler is cooled by seawater whereas the jacket-water to cool a land-based aftercooler is cooled by ambient air. Due to their operating environment, marine engines typically have a virtually unlimited supply of cool water for onboard cooling. The limited space in marine engine compartments and the fact that engine rooms are often located deep within the vessel dictates that engine heat be discharged to seawater rather than to ambient air. Several configurations relating the engine, turbocharger, aftercooler, and heat exchanger are possible. Three different configurations are explained and analyzed for relative costs below.

**Case 1: Engine with Onboard Heat Exchanger**

The first case is the simplest case - a naturally-aspirated engine and onboard heat exchanger. There is no turbocharger and no aftercooler associated with this configuration. Seawater is strained and brought into the heat exchanger to cool the jacket-water. The jacket-water passes from the heat exchanger to the engine and back thereby cooling the engine. This configuration is generally found on older propulsion engines and most auxiliary engines rated under 100 horsepower. Although combustion chamber design and the fuel delivery system can be optimized to increase power and reduce emissions, it is generally expected that naturally-aspirated engines will have a difficult time meeting the new, proposed emission standards.

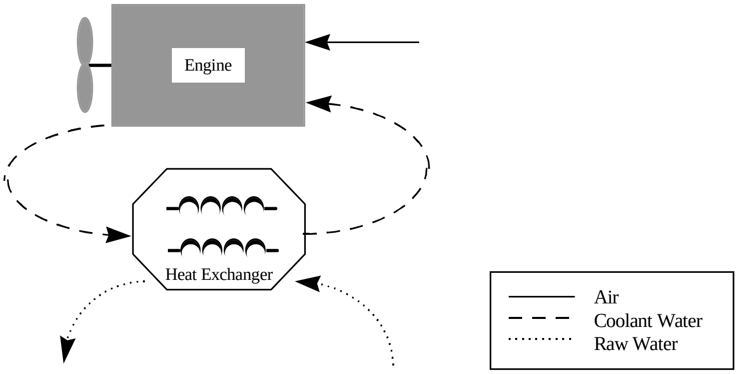

Figure 1: Example of a naturally-aspirated engine with a heat exchanger (or keel cooler) (Case 1)

**Case 2: Turbocharger and Aftercooler in the Engine Coolant Loop**

The first aftercooler configuration is shown in Figure 2. This case is a turbocharged and aftercooled version of the Case 1 configuration. The aftercooler is integrated into the engine's coolant loop. Thus, the same coolant that cycles between the onboard heat exchanger or keel cooler and the engine is also circulated through the aftercooler, and the coolant that absorbs heat from the engine block also absorbs heat from the aftercooler. This approach is regularly used in CI marine propulsion engines and large auxiliary engines.

The main advantage of a Case 2 configuration is the increased power-to-weight ratio due to the advantages of turbocharging and aftercooling. Although specific values vary between model lines, there is also a decrease in BSFC and a decrease in NOx emissions over a Case 1 engine. Another advantage is that design, installation, operation, and maintenance of Case 2 systems is generally well established and well supported by the engine manufacturers, ship builders, and vessel operators.

The main drawback of conventional aftercooling is that the charge air temperature rarely drops below 180°F. The coolant water enters the onboard heat exchanger or keel cooler at roughly 180-200°F and drops 10 to 15°F. After compression in the turbocharger, the charge air is at 300 to 350°F. The engine coolant leaving the heat exchanger is at approximately 180°F, so the charge air temperature is typically lowered to 220 to 240°F. The cooler the charge air, the more dense it is and the more air can be drawn into the cylinder per stroke. More air at lower temperatures generally supports a larger power-to-weight ratio for the engine and reduced NOx emissions.

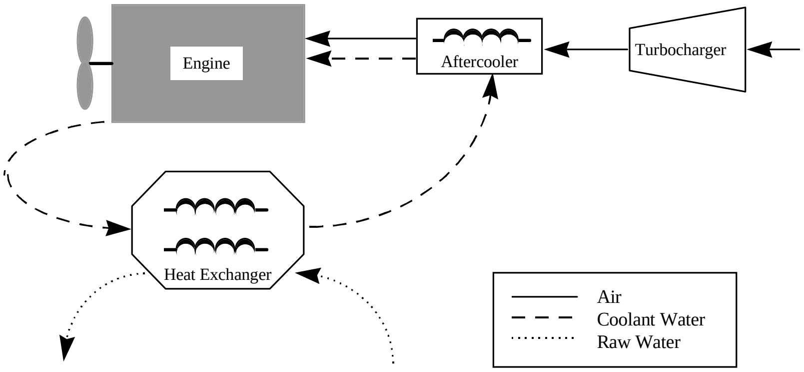

Figure 2: Example of a turbocharger and aftercooler in the same engine coolant loop (Case 2)

**Case 3: Separate-circuit Aftercooler**

A cooling technology that takes advantage of the vast resource of cool water available to marine engines is a separate-circuit aftercooler. In this configuration, a completely separate coolant loop is formed that consists of the aftercooler, a small heat exchanger, a coolant pump, and associated plumbing. The conventional cooling circuit consisting of a larger heat exchanger, a coolant pump, and associated plumbing is very similar to that described for Case 2. Both circuits can use the same raw water pump; the raw water would then simply be split before the heat exchangers to send a fraction to the aftercooler's heat exchanger and the rest to the engine's heat exchanger. The concept of separate-circuit aftercooling is illustrated in Figure 3.

Separate-circuit aftercooling provides the same advantages as those described for jacket-water aftercooling (Case 2), but to a greater degree. Since the separate-circuit heat exchanger can cool the charge air to within 30°F of the seawater, charge air temperatures can be controlled to optimum levels.

The disadvantages of separate-circuit aftercooling are the additional costs of hardware and the additional complexity of two separate cooling systems. However, the anticipated improvements in BSFC are likely to lead to significant savings in the total life-cycle costs of the system. There is also some concern among engine manufacturers that lowering the charge air temperature below 130°F will lead to condensation in the charge air and the possibility of increased wear on the engine. More research may be necessary to address this concern and, if it is found to be valid, a thermostat with a proportioning bypass valve could be installed with the separate-circuit to control the flow of seawater and thereby control the temperature of the charge air.

A variation of separate-circuit aftercooling is commonly used for recreational CI marine engines. Commonly referred to as direct seawater aftercooling, this configuration involves routing seawater directly through the aftercooler. This achieves maximum cooling of the charge air and reduces cost by eliminating the intermediate heat exchanger but technical drawbacks prevent this from being used in commercial applications. The principal concern is for the increase in maintenance costs to address corrosion of the more extensive seawater plumbing and the potential for catastrophic failure if a pipe would fail in the engine or engine room. Because direct seawater aftercooling is not projected for commercial applications and is already widely used for recreational applications, no increased use of seawater aftercooling is anticipated to result from new emission standards. This report therefore does not include estimated costs for this technology.

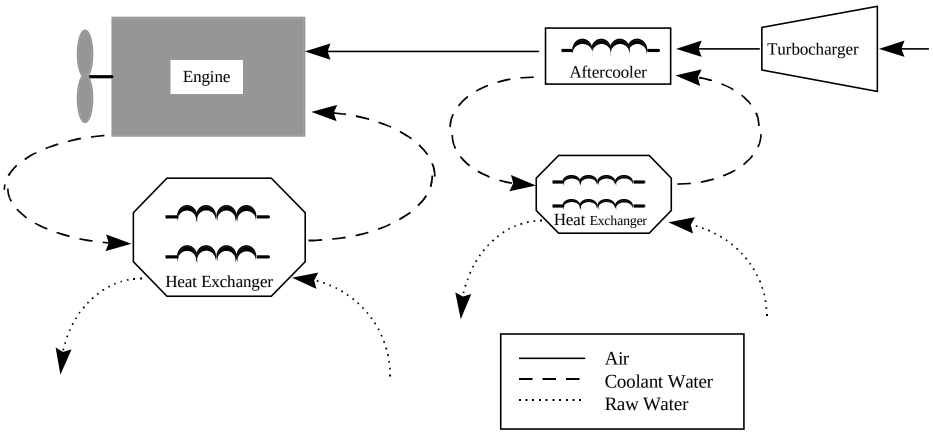

Figure 3: Example of a separate-circuit aftercooler (Case 3A)

A detailed description of the technology and hardware associated with these turbocharging and aftercooling configurations are presented below. The attached spreadsheets in Tables A-1 through A-5 in the appendix show the costs for engines ranging from 130 to 4,000 nominal horsepower (100 to 3,000 kW). The 130 and 500 horsepower (100 and 400 kW) engines are derived from technology used in land-based nonroad engines that in turn are derived from highway engine technology. The 1,000 and 2,000 horsepower (750 and 1,500 kW) engines are derived from land-based off-road engine technology. The 4,000 horsepower (3,000 kW) engine is derived from locomotive engine technology.

## COST METHODOLOGY

The costs for different aspiration and cooling technologies are presented to provide information on marine-specific incremental costs. Representative models were chosen from the test case power ranges studied for this report. No single model was used for developing all cost information in this report, but rather a composite engine with characteristics of all the representative models in the applicable power range was used. Engines were considered from Cummins, Caterpillar, Detroit Diesel, Electromotive Division of General Motors, Daytona, John Deere, and Warstila NSD. Models from these manufacturers were chosen to give structure to the data collection process and are not included for endorsement purposes.

Hardware costs depend on the individual engine model complexity and volume sold. Average engine or vessel parameters and configurations were used to develop the costs. For example, an engine with 16 or more cylinders will have multiple turbochargers and aftercoolers while a more compact engine of the same power output might only have one turbocharger and aftercooler. Another example is the cost of plumbing. A tugboat will have high-power engines in a very compact setting which requires minimal lengths of piping while a similar high-power engine used for auxiliary power on a large ocean-going vessel may be located several decks away from the heat exchanger cooling system thereby requiring a much larger amounts of piping. All costs are reported in 1997 dollars.

Assembler labor rates were obtained from U.S. Department of Labor (DOL) statistics for the Michigan and Midwest regions [1] and inflated to 1997 dollars using DOL labor cost indices [2]. Based on this information, labor rates used in this report are $17.50 per hour plus a 60 percent fringe rate providing a cost of direct labor of $28 per hour.

In most cases, estimated component costs were based on either the discounted retail price of replacement parts or were built up from models developed by ARCADIS Geraghty & Miller. Much of the hardware and cost information was gathered from engine manufacturers, component manufacturers, and shipbuilders. Where discounted prices of replacement parts were used, estimates of supplier component prices were determined from retail prices for replacement parts. These prices were discounted to 33 percent of the retail price for use in the equations for calculating the retail price equivalent. Lindgren [3] discounted retail prices to 20 or 25 percent for use in his calculations. Although the low sales volumes and the specialty nature of many technologies in the marine industry may lead to higher markups, it is the belief of the authors that 33 percent is more realistic in today's competitive retail market. If a different markup can be quantified, the cost estimates in Tables 2 through 6 should be adjusted accordingly.

Discounted retail prices already include the costs of the supplier raw materials, supplier labor and labor overhead, and a reasonable markup for the supplier. Labor overhead in these analyses is assumed to be 40 percent of the cost of direct labor as cited in Lindgren [3]. Manufacturer overhead and manufacturer profit, when added together, are assumed to be 29 percent as cited by Jack Faucett Associates [4]. The general formula used to determine the component cost to the manufacturer is:

$$\text{Component Cost} = \{M + L * 1.4\} * 1.29$$

where:

M = Total Hardware Cost to the Manufacturer (materials) and

L = Labor (to install the components on the engine and on the vessel)

Fixed costs will include extensive efforts to test and map engine performance in the new marine configuration. Fixed costs included in this report are those that are incremental to the costs that a Case 1 engine would require. These costs reflect efforts to maximize aftercooler and turbocharger effects on the engine performance and the additional testing required to develop performance characteristics for the separate-circuit aftercooler technology which requires a greater degree of development.

The estimates presented in this report represent costs in the first year of production of components on a nationwide scale. Production costs related to direct and indirect labor are likely to fall in subsequent years as workers gain skill, develop shortcuts, and improve the flow of tasks. Costs for materials are also likely to decline over time, although not as rapidly as labor costs due to methods for reducing waste or using lower cost materials.

## TECHNOLOGY

**Turbocharger**: Turbochargers used on marine engines must operate with reduced surface temperatures and are therefore typically cooled using engine coolant, which substantially increases their cost. The sophistication and performance of turbochargers for marine engines varies widely which makes it difficult to precisely estimate turbocharger costs over a wide range of engine models. Turbocharger costs were estimated based on a quote from a turbocharger manufacturer that turbochargers for engines in the horsepower ranges 400 to 2,000 horsepower (300 to 1,500 kW) are sold for $1.50 per engine horsepower in bulk shipments of greater than 1,000 pieces to the original engine manufacturer (OEM). The factor used in the calculations was $1.60 per turbocharger to account for some smaller volume sales or slightly more sophisticated technologies.

Dual turbochargers and even quadruple turbochargers are used in some applications, usually for engines with 12 or more cylinders. Some locomotive-sized engines have 16 or 20 cylinders and therefore use four turbocharger/aftercooler combinations, one for each set of 4 or 5 cylinders. This reduces pumping losses and reduces the overall equipment size. In this report, the engines rated at 2,000 horsepower (1,500 kW) were treated as having dual turbochargers of total cost of $1.90 per engine horsepower. The 4,000 horsepower (3,000 kW) engines were costed to have four turbochargers, each one servicing one quarter of the total engine horsepower at $1.90 per horsepower. Information from some manufacturers suggests that turbochargers for large medium-speed engines will be significantly more expensive, ranging from $25,000 to $100,000 apiece for rebuilt and new turbochargers, respectively. If a discount factor of one third is applied to these prices to account for engine and equipment supplier markups, supplier costs range from approximately $8,300 to $33,000, which falls within the range of the costs used in this report.

**Cooling System**: The total cooling system cost is the sum of the aftercooler, heat exchanger, raw water pump, plumbing, coolant, coolant pump, thermostat and wiring costs, as estimated below.

*Aftercooler:* Aftercooler costs were estimated from supplier price estimates and from aftermarket prices from parts suppliers discounted to one third of retail price. The factor used to determine nominal aftercooler cost in the calculations was $1.35 per engine horsepower. Aftercooler costs for were increased by 10 percent over Case 2 to account for more durable materials and extra manufacturing costs that might be required to produce an aftercooler capable of withstanding larger temperature changes.

*Heat Exchanger*: Heat exchanger costs were estimated for units that used copper-nickel tube bundles and copper shells. Copper-nickel is often used with seawater as it is corrosion resistant and has a high heat transfer coefficient. As other corrosion resistant materials are also used to make heat exchangers, the prices in this report can be scaled using a ratio of the alternate metal’s cost to the cost for copper-nickel. Price estimates were based on engineering calculations conducted by ARCADIS Geraghty and Miller and verified by price estimates from independent heat exchanger manufacturers. The factor used here was $1.85 per engine horsepower for the heat exchanger used with the Case 1 engine. This cost was increased by 25% to $2.30 per engine horsepower for Case 2. The cost for a Case 2 heat exchanger was increased by 50% to $3.45 to account for the addition of a second heat exchanger of approximately half the size in Case 3.

A keel cooler could be used in place of a heat exchanger. A simple way to visualize a keel cooler is to picture a heat exchanger mounted on the hull of the vessel under the water line. Coolant fluid is piped to the keel cooler and raw water flows by on the outside of the unit. In this way, no raw water is brought into the vessel. If a vessel owner wants a keel cooler, it is usually designed as part of a new vessel as keel coolers are a difficult retrofit option. The keel cooler is slightly more expensive than a standard, OEM-supplied heat exchanger but requires less maintenance as there is no internal fouling of tube bundles, raw water pipes, or raw water pumps. The keel cooler is also safer since no seawater is pumped into the ship. However, a keel cooler may not be able to support the cooling needs of larger engines. The efficiency of a keel cooler is often less than that of a heat exchanger as the wall thickness of a keel cooler is greater that the tube thickness of a heat exchanger and thus has more resistance to heat transfer. The weight of a keel cooler is also a concern for some vessel operators.

*Raw Water/Seawater Pump*: When an internal heat exchanger is used, a pump is required to bring the seawater into the heat exchanger bundles. The rate of seawater flow is often similar for engines under 1,000 horsepower (750 kW). Pump costs are based on estimates from vendors who supply pumps to the OEM for installation on the engine. Raw water pumps are engine driven and do not require separate motors, controls, or additional wiring. Smaller horsepower engines with lower operating hours often use a rubber impeller pump with a bronze housing. Larger engines that require higher flowrates or engines that are operated for the long hours, typical of commercial applications, often use centrifugal pumps with bronze blades and housings.

The same price estimates were used for Case 1 and Case 2 raw water pumps. This is reasonable because the added heat load of the turbocharger and aftercooler is carried by increasing the flow rate (within the allowable boundaries of the existing pump) and upgrading the efficiency of the heat exchanger. For the upgrade to a separate-circuit aftercooler, the analysis assumes that the raw water pump will need to be upgraded to the next flow rate level. The addition of a separate-circuit aftercooler is expected to add 30 gpm to the Case 2 flow rate for engines under 1,000 horsepower (750 kW) and 60 gpm for engines greater than 2,000 horsepower (1,500 kW). The base price is $500 for a pump rated at 100 gpm plus an additional $100 for each additional 30 gpm.

*Coolant/Fresh Water Pump*: The coolant fluid pump is a centrifugal pump powered by the engine. No changes will need to be made to this pump between Cases 1 and 2. Case 3 requires the addition of a separate coolant pump. This pump will be a small fraction of the size and cost of the primary coolant pump. Pump prices are based on aftermarket parts suppliers, discounted to 1/3 of their listed price.

*Plumbing*: Plumbing consists of all the pipes and hoses used for the raw water circuit and the coolant water circuit. The raw water circuit brings seawater into the heat exchanger and returns it slightly warmer after it has circulated through the heat exchanger. The coolant loop carries coolant to the engine pump from the heat exchanger and then for the Case 2 configuration, carries part of the coolant to the aftercooler and part to the engine. The heated coolant then returns to the heat exchanger. Engines in the 130 and 500 nominal horsepower (100 and 400 kW) ranges are compact units with the aftercooler, turbocharger, and heat exchanger all mounted on or very close to the engine block. Thus, the lengths of coolant piping for these engines are small and not likely to add much cost to the overall system. For the 500 horsepower (400 kW) engine, a total of 10 feet of 2" OD steel pipe at $1.20 per foot was used for the coolant loop in Case 1, 10 feet in Case 2, and 20 feet in Case 3. The raw water circuit used a total of 20 feet in Case 1 and 20 feet in Case 2 of 2" copper-nickel pipe at $3.60 per foot. Case 3 used 40 feet of the same pipe to feed raw water to the two heat exchanger circuits. Larger engines (greater than 1,000 horsepower (750 kW)) will sometimes have auxiliary systems such as heat exchangers mounted in other compartments or even in other decks of the ship than the main propulsion engine(s). More extensive lengths of piping were costed for the larger engines (e.g. up to 160 feet of 4" copper tubing for a 4,000 horsepower (3,000 kW) engine).

*Coolant*: Ethylene glycol and water are mixed to create the coolant fluid. As more coolant will be needed for the separate-circuits of Case 3, coolant costs are included in the incremental cost estimates. The concentration of ethylene glycol in the coolant varies depending on the use of the vessel and the climate it most frequently operates in. For this study, mixed coolant was estimated at $0.50 per gallon with coolant tanks varying from 30 to 150 gallons.

*Thermostat*: Thermostat costs are expected to increase modestly or not at all between the various cases. While the algorithms governing thermostatic controls may change with the addition of turbochargers and aftercoolers to the engine, it is not expected that the actual thermostat hardware will change or that an additional thermostat will be required.

*Wiring*: Estimated wiring costs varied widely in our investigation. While one manufacturer stated that nearly $500 worth of wiring needed to be added on an aftercooled, turbocharged, and electronically controlled engine, other estimates were much lower. For these cost analyses, ARCADIS Geraghty and Miller treated the $500 cost as though it included both for the wire and the installation labor. Actual costs of wire in this report are $10 to $25 depending on the size of the engine with additional costs factored into the installation labor costs for each case.

## FIXED COSTS

Fixed costs are included to show the development costs incremental to the Case 1 baseline that will be required for Case 2 and Case 3 engines. These incremental costs are for such efforts as adjusting and fitting the water cooled manifold system, the water cooled turbocharger, and the aftercooler system to the engine as well as costs for lab tests and field tests of engine performance. Although Case 2 technologies already exist in land-based nonroad engines of equivalent power ratings, their transfer to marine applications will require additional development costs such as testing and setting the injection characteristics of the engine over those required for the land-based engine.

Fixed costs are calculated based on the development costs per model line obtained by conversations with several engine manufacturers. Fixed costs per model line range from $400,000 to $1.4

million depending on the degree of redesign and the size of the engine. Higher costs are expected for larger engines due to the additional expense of fabricating prototype parts and conducting engine tests. These development costs per model line are amortized over 5 years at seven percent interest per annum. Fixed costs per engine are found by taking the amortized development costs per model line, dividing by the engine sales per year, and multiplying by the model lines in the power range. Some manufacturers have indicated that there will be fewer model lines for engines meeting new emission standards. While a reduction in model lines has not been included in the fixed cost estimates of this report, streamlined production offerings would result in reduced fixed costs per engine.

## IMPROVEMENTS IN BRAKE SPECIFIC FUEL CONSUMPTION

As described earlier, turbocharging and aftercooling an engine improve the engine's BSFC. Lifetime fuel cost savings for each one percent improvement in BSFC are detailed in Table A-6 and summarized in Table 2. Baseline BSFC numbers were obtained from marketing information available from Cummins, EMD and DDC for engines in the test case engine horsepower ranges. Load factors, annual hours of operation, and engine lifetime were obtained from Power Systems Research and are expected to be representative for the test case engines. The average cost per gallon of API 35 fuel was based on EPA estimates of nationwide fuel prices at $0.65 per gallon. If fuel prices increase over time, the value of the BSFC improvement will increase correspondingly.

Table 2 - Lifetime Savings From One Percent Improvement in BSFC

| | **130 hp** | **500 hp** | **1,000 hp** | **2,000 hp** | **4,000 hp** |
|---|---:|---:|---:|---:|---:|
| **Commercial** | $781 | $3,626 | $7,857 | $20,049 | $46,257 |
| **Auxiliary** | $613 | $2,561 | $4,641 | $9,159 | $18,560 |

Annual fuel costs per engine were determined by multiplying the BSFC by the estimated annual operating hours, load factor, rated horsepower, and cost of fuel per gallon then dividing by fuel density. This annual cost was then extended over the expected lifetime of the engine and brought to the net present value of money using a seven percent interest discount rate.

## RESULTS

Table 3 presents the total and incremental costs associated with each of the nominal test case engines examined in this study. More detailed analysis is available in the Appendix.

Table 3 - Estimated System and Incremental Cost Estimates

| Engine Power Ranges (Hp) | Nominal Engine Power (Hp) | Case 1 | | Case 2 | | Case 3 | |
|---|---|---|---|---|---|---|---|
| | | System | Incremental | System | Incremental | System | Incremental |
| 50 - 300 | 130 | $2,582 | -- | $4,236 | $1,655 | $5,167 | $2,585 |
| 300 - 750 | 500 | $4,417 | -- | $9,954 | $5,536 | $12,493 | $8,075 |
| 750 - 1,500 | 1,000 | $8,688 | -- | $26,436 | $17,748 | $32,721 | $24,032 |
| 1,500 - 2,500 | 2,000 | $14,972 | -- | $41,391 | $26,419 | $50,943 | $35,971 |
| 2,500 - 6,000 | 4,000 | $25,058 | -- | $70,715 | $45,657 | $86,427 | $61,369 |

## REFERENCES

1. "Industry Wage Survey: Motor Vehicles and Parts 1989," U.S. Department of Labor, Bureau of Labor Statistics, October 1991, Bulletin 2384, page 7.

2. "Employment Cost Indexes and Levels, 1975-1994," U.S. Department of Labor, Bureau of Labor Statistics, September 1994, Bulletin 2447, page 65.

3. Lindgren, Leroy H., "Cost Estimations for Emission Control Related Components/Systems and Cost Methodology Description," Rath & Strong, Inc., Report No. EPA 460/3-78-002, December 1977.

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

# APPENDIX

Explanatory notes for Tables A-1 through A-5

- Case 1: Naturally-Aspirated Engine with Onboard Heat Exchanger
- Case 2: Engine with Turbocharger and Aftercooler in the Engine Coolant Loop
- Case 3: Separate Circuit Aftercooler
- Raw water pump may require an upgrade for Case 2 if flows need to increase appreciably due to aftercooler heat load. In most cases, it will be sufficient to increase the effectiveness of the heat exchanger.
- Development costs included above are for marine specific development. Costs for electronic controls and combustion optimization already included in the development of the equivalent industrial and locomotive engines.
- Engines per year for Case 2 and Case 3 are a sum of auxiliary and commercial sales as projected by PSR for the horsepower range.
- Number of Heat Exchangers Required - The line item price for Case 3 is the combined price for both units.

Table A-1: Incremental Costs for marine diesel engine technology improvements, 50 to 300 HP

| **Nominal Engine hp** | 130 | | # Cylinders | 4 |
|---|---|---|---|---|
| **Hardware Cost to Manufacturer** | | **Case 1** | **Case 2** | **Case 3** |
| Turbocharger (each) | | $0 | $208 | $208 |
| Number Required | | 0 | 1 | 1 |
| Aftercooler (each) | | $0 | $176 | $194 |
| Number Required | | 0 | 1 | 1 |
| Heat Exchanger (total) | | $227 | $284 | $426 |
| Number Req. (see explanatory note) | | 1 | 1 | 2 |
| Fresh Water Pump | | $91 | $91 | $137 |
| Raw Water Pump | | $225 | $225 | $325 |
| Piping Total | | $44 | $44 | $90 |
| Fresh water Pipe @ 2" | feet | 6 | 6 | 8 |
| | total fresh water pipe cost | $7 | $7 | $10 |
| Raw Water Pipe @ 2" | feet | 10 | 10 | 22 |
| | total raw water pipe cost | $36 | $36 | $80 |
| Coolant | | $8 | $8 | $13 |
| Thermostat | | $15 | $15 | $15 |
| Wiring | feet | 50 | 55 | 60 |
| | cost | $20 | $25 | $27 |
| **Total Hardware Cost** | | **$630** | **$1,075** | **$1,434** |
| | **Assembly** | | | |
| Labor @ $28/hr | hours | 35 | 40 | 46 |
| | total labor cost | $980 | $1,120 | $1,288 |
| Overhead @ 40% | | $392 | $448 | $515 |
| Total Assembly Cost | | $1,372 | $1,568 | $1,803 |
| Markup on Hardware and Assembly @ 29% | | $580 | $767 | $939 |
| **Total Component Costs** | | **$2,582** | **$3,410** | **$4,176** |
| | **Fixed Costs** | | | |
| Development Costs Per Model Line | | | $400,000 | $480,000 |
| Engine Sales Per Year | | | 3284 | 3284 |
| Model Lines in Horsepower Range | | | 26 | 26 |
| Years To Recover | | | 5 | 5 |
| **Fixed cost/engine** | | | $826 | $992 |
| **Total Costs/engine** | | **$2,582** | **$4,236** | **$5,167** |
| **Total Incremental Costs** | | **$0** | **$1,655** | **$2,585** |

Table A-2: Incremental Costs for marine diesel engine technology improvements, 300 to 750 HP

| | | | | |
|---|---|---|---|---|
| **Nominal Engine hp** | 500 | | # Cylinders | 6 |
| **Hardware Cost to Manufacturer** | | **Case 1** | **Case 2** | **Case 3** |
| Turbocharger (each) | | $0 | $800 | $800 |
| Number Required | | 0 | 1 | 1 |
| Aftercooler (each) | | $0 | $677 | $745 |
| Number Required | | 0 | 1 | 1 |
| Heat Exchanger (total) | | $874 | $1,092 | $1,638 |
| Number Req. (see explanatory note) | | 1 | 1 | 2 |
| Fresh Water Pump | | $137 | $137 | $227 |
| Raw Water Pump | | $500 | $500 | $600 |
| Piping Total | | $85 | $85 | $170 |
| Fresh water Pipe @ 2" | feet | 10 | 10 | 20 |
| | total fresh water pipe cost | $12 | $12 | $24 |
| Raw Water Pipe @ 2" | feet | 20 | 20 | 40 |
| | total raw water pipe cost | $73 | $73 | $146 |
| Coolant | | $15 | $15 | $25 |
| Thermostat | | $15 | $15 | $15 |
| Wiring | feet | 50 | 55 | 60 |
| | cost | $35 | $38 | $40 |
| **Total Hardware Cost** | | **$1,660** | **$3,359** | **$4,260** |
| | **Assembly** | | | |
| Labor @ $28/hr | hours | 45 | 50 | 65 |
| | total labor cost | $1,260 | $1,400 | $1,820 |
| Overhead @ 40% | | $504 | $560 | $728 |
| Total Assembly Cost | | $1,764 | $1,960 | $2,548 |
| Markup on Hardware and Assembly @ 29% | | $993 | $1,543 | $1,974 |
| **Total Component Costs** | | **$4,417** | **$6,862** | **$8,782** |
| | **Fixed Costs** | | | |
| Development Costs Per Model Line | | | $550,000 | $660,000 |
| Engine Sales Per Year | | | 1579 | 1579 |
| Model Lines in Horsepower Range | | | 15 | 15 |
| Years To Recover | | | 2 | 2 |
| **Fixed cost/engine** | | | $3,092 | $3,711 |
| **Total Costs/engine** | | **$4,417** | **$9,954** | **$12,493** |
| **Total Incremental Costs** | | **$0** | **$5,536** | **$8,075** |

Table A-3: Incremental Costs for marine diesel engine technology improvements, 750 to 1,500 HP

| **Nominal Engine hp** | 1000 | | # Cylinders | 8 |
|---|---|---|---|---|
| **Hardware Cost to Manufacturer** | | **Case 1** | **Case 2** | **Case 3** |
| Turbocharger (each) | | $0 | $1,600 | $1,600 |
| Number Required | | 0 | 1 | 1 |
| Aftercooler (each) | | $0 | $1,355 | $1,490 |
| Number Required | | 0 | 1 | 1 |
| Heat Exchanger (total) | | $1,747 | $2,184 | $3,276 |
| Number Req. (see explanatory note) | | 1 | 1 | 2 |
| Fresh Water Pump | | $232 | $232 | $369 |
| Raw Water Pump | | $1,000 | $1,000 | $1,200 |
| Piping Total | | $128 | $128 | $255 |
| Fresh water Pipe @ 2" | feet | 15 | 15 | 30 |
| | total fresh water pipe cost | $18 | $18 | $36 |
| Raw Water Pipe @ 3" | feet | 30 | 30 | 60 |
| | total raw water pipe cost | $109 | $109 | $219 |
| Coolant | | $35 | $35 | $43 |
| Thermostat | | $25 | $25 | $25 |
| Wiring | feet | 55 | 60 | 65 |
| | cost | $40 | $42 | $44 |
| **Total Hardware Cost** | | **$3,207** | **$6,601** | **$8,302** |
| | **Assembly** | | | |
| Labor @ $28/hr | hours | 90 | 100 | 130 |
| | total labor cost | $2,520 | $2,800 | $3,640 |
| Overhead @ 40% | | $1,008 | $1,120 | $1,456 |
| Total Assembly Cost | | $3,528 | $3,920 | $5,096 |
| Markup on Hardware and Assembly @ 29% | | $1,953 | $3,051 | $3,885 |
| **Total Component Costs** | | **$8,688** | **$13,572** | **$17,284** |
| | **Fixed Costs** | | | |
| Development Costs Per Model Line | | | $700,000 | $840,000 |
| Engine Sales Per Year | | | 142 | 142 |
| Model Lines in Horsepower Range | | | 10 | 10 |
| Years To Recover | | | 5 | 5 |
| **Fixed cost/engine** | | | $12,864 | $15,437 |
| **Total Costs/engine** | | **$8,688** | **$26,436** | **$32,721** |
| **Total Incremental Costs** | | **$0** | **$17,748** | **$24,032** |

Table A-4: Incremental Costs for marine diesel engine technology improvements, 1,500 to 2,500 HP

| **Nominal Engine hp** | 2000 |  | # Cylinders | 16 |
|---|---|---|---|---|
| **Hardware Cost to Manufacturer** |  | **Case 1** | **Case 2** | **Case 3** |
| Turbocharger (each) |  | $0 | $1,778 | $1,778 |
| Number Required |  | 0 | 2 | 2 |
| Aftercooler (each) |  | $0 | $1,505 | $1,656 |
| Number Required |  | 0 | 2 | 2 |
| Heat Exchanger (total) |  | $3,495 | $4,368 | $6,552 |
| Number Req. (see explanatory note) |  | 1 | 1 | 2 |
| Fresh Water Pump |  | $395 | $395 | $532 |
| Raw Water Pump |  | $2,000 | $2,000 | $2,200 |
| Piping Total |  | $310 | $310 | $620 |
| Fresh water Pipe @ 3" | feet | 45 | 45 | 90 |
|  | total fresh water pipe cost | $55 | $55 | $109 |
| Raw Water Pipe @ 3" | feet | 70 | 70 | 140 |
|  | total raw water pipe cost | $255 | $255 | $510 |
| Coolant |  | $45 | $45 | $60 |
| Thermostat |  | $25 | $25 | $25 |
| Wiring | feet | 65 | 70 | 75 |
|  | cost | $45 | $48 | $52 |
| **Total Hardware Cost** |  | **$6,314** | **$13,757** | **$16,908** |
|  | **Assembly** |  |  |  |
| Labor @ $28/hr | hours | 135 | 150 | 195 |
|  | total labor cost | $3,780 | $4,200 | $5,460 |
| Overhead @ 40% |  | $1,512 | $1,680 | $2,184 |
| Total Assembly Cost |  | $5,292 | $5,880 | $7,644 |
| Markup on Hardware and Assembly @ 29% |  | $3,366 | $5,695 | $7,120 |
| **Total Component Costs** |  | **$14,972** | **$25,332** | **$31,672** |
|  | **Fixed Costs** |  |  |  |
| Development Costs Per Model Line |  |  | $1,000,000 | $1,200,000 |
| Engine Sales Per Year |  |  | 130 | 130 |
| Model Lines in Horsepower Range |  |  | 8 | 8 |
| Years To Recover |  |  | 5 | 5 |
| **Fixed cost/engine** |  |  | $16,059 | $19,271 |
| **Total Costs/engine** |  | **$14,972** | **$41,391** | **$50,943** |
| **Total Incremental Costs** |  | **$0** | **$26,419** | **$35,971** |

Table A-5: Incremental Costs for marine diesel engine technology improvements, 2,500 to 6,000 HP

| **Nominal Engine hp** | 4000 | | # Cylinders | 20 |
|---|---|---|---|---|
| **Hardware Cost to Manufacturer** | | **Case 1** | **Case 2** | **Case 3** |
| Turbocharger (each) | | $0 | $2,133 | $2,133 |
| Number Required | | 0 | 4 | 4 |
| Aftercooler (each) | | $0 | $1,594 | $1,753 |
| Number Required | | 0 | 4 | 4 |
| Heat Exchanger (total) | | $6,989 | $8,737 | $13,105 |
| Number Req. (see explanatory note) | | 1 | 1 | 2 |
| Fresh Water Pump | | $671 | $671 | $871 |
| Raw Water Pump | | $2,800 | $2,800 | $3,200 |
| Piping Total | | $401 | $401 | $729 |
| Fresh water Pipe @ 3" | feet | 60 | 60 | 120 |
| | total fresh water pipe cost | $73 | $73 | $146 |
| Raw Water Pipe @ 4" | feet | 90 | 90 | 160 |
| | total raw water pipe cost | $328 | $328 | $583 |
| Coolant | | $75 | $75 | $100 |
| Thermostat | | $500 | $500 | $500 |
| Wiring | feet | 75 | 85 | 95 |
| | cost | $50 | $55 | $60 |
| **Total Hardware Cost** | | **$11,487** | **$28,148** | **$34,112** |
| Assembly | | | | |
| Labor @ $28/hr | hours | 203 | 225 | 293 |
| | total labor cost | $5,670 | $6,300 | $8,190 |
| Overhead @ 40% | | $2,268 | $2,520 | $3,276 |
| Total Assembly Cost | | $7,938 | $8,820 | $11,466 |
| Markup on Hardware and Assembly @ 29% | | $5,633 | $10,721 | $13,218 |
| **Total Component Costs** | | **$25,058** | **$47,689** | **$58,796** |
| | **Fixed Costs** | | | |
| Development Costs Per Model Line | | | $1,200,000 | $1,440,000 |
| Engine Sales Per Year | | | 68 | 68 |
| Model Lines in Horsepower Range | | | 5 | 5 |
| Years To Recover | | | 5 | 5 |
| **Fixed cost/engine** | | | $23,026 | $27,631 |
| **Total Costs/engine** | | **$25,058** | **$70,715** | **$86,427** |
| **Total Incremental Costs** | | **$0** | **$45,657** | **$61,369** |

## Table A-6: Lifetime fuel savings estimated for a one percent improvement in brake specific fuel consumption

| Load Factors, % of hp | 150 | 400 | 750 | 2000 | 5000 |
|---|---|---|---|---|---|
| Recreational | 30% | 30% | 40% | -- | -- |
| Commercial | 69% | 71% | 73% | 79% | 81% |
| Auxillary | 65% | 65% | 65% | 65% | 65% |
| | | | | | |
| **Annual Operating Hours, hr/yr** | 150 | 400 | 750 | 2000 | 5000 |
| Recreational | 225 | 225 | 500 | -- | -- |
| Commercial | 3000 | 3241 | 3769 | 4503 | 5000 |
| Auxillary | 2500 | 2500 | 2500 | 2500 | 2500 |
| | | | | | |
| **Lifetime, yr** | 150 | 400 | 750 | 2000 | 5000 |
| Recreational | 13 | 13 | 13 | -- | -- |
| Commercial | 15 | 15 | 15 | 15 | 15 |
| Auxillary | 17 | 17 | 17 | 17 | 17 |
| | | | | | |
| **Avg BSFC, lb/hp-hr** | 130 | 500 | 1000 | 2000 | 4000 |
| Commercial | 0.343 | 0.373 | 0.338 | 0.333 | 0.338 |
| 1% Improvement | 0.340 | 0.369 | 0.334 | 0.330 | 0.334 |

Avg Fuel Cost
Cost 35 API $ 0.65/gallon Density 7.001 lb/gal

Fuel Savings with PV of money

| | | | 130 hp | 500 hp | 1000 hp | 2000 hp | 4000 hp |
|---|---|---|---|---|---|---|---|
| **Commercial** | Pre | | $8,576 | $39,814 | $86,270 | $220,132 | $507,875 |
| | | 1% | $8,491 | $39,415 | $85,407 | $217,930 | $502,796 |
| Present Value | Pre | | $78,114 | $362,619 | $785,737 | $2,004,940 | $4,625,678 |
| | | 1% | $77,333 | $358,993 | $777,879 | $1,984,891 | $4,579,421 |
| Savings | $/lifetime | | $781 | $3,626 | $7,857 | $20,049 | $46,257 |
| | | | | | | | |
| **Recreational** | Pre | | $285 | $1,191 | $6,396 | | |
| | 1% | | $282 | $1,179 | $6,332 | | |
| Present Value | Pre | | $2,598 | $10,850 | $58,258 | $0 | $0 |
| | | 1% | $2,572 | $10,741 | $57,676 | $0 | $0 |
| Savings | $/lifetime | | $26 | $108 | $583 | $0 | $0 |
| | | | | | | | |
| **Auxillary** | Pre | | $6,733 | $28,116 | $50,952 | $100,556 | $203,777 |
| | | 1% | $6,665 | $27,834 | $50,443 | $99,550 | $201,739 |
| Present Value | Pre | | $61,321 | $256,075 | $464,068 | $915,853 | $1,855,982 |
| | | 1% | $60,708 | $253,514 | $459,427 | $906,694 | $1,837,422 |
| Savings | $/lifetime | | $613 | $2,561 | $4,641 | $9,159 | $18,560 |

**Summary**

| | | | | | | |
|---|---|---|---|---|---|---|
| **Recreational** | $/lifetime | $ 26 | $ 108 | $ 583 | $ - | $ - |
| **Commercial** | $/lifetime | $ 781 | $ 3,626 | $ 7,857 | $ 20,049 | $ 46,257 |
| **Auxillary** | $/lifetime | $ 613 | $ 2,561 | $ 4,641 | $ 9,159 | $ 18,560 |

Sample Calculation:

Annual Payment = (Avg BSFC) * (Nominal hp) * (Load Factor) * (Annual hr of operation) / (Density) * (Cost 35 API)

Savings = (Pre Present Value) - (1% Present Value)

Table A-7: Heat Rejection

| | Engine Horespower | | | | |
|---|---|---|---|---|---|
| **Heat Rejected** | **130** | **500** | **1000** | **2000** | **4000** |
| Case 1: engine only (kW) | 98 | 375 | 740 | 1200 | 2200 |
| Case 2: engine & aftercooler -conventional (kW) | 228 | 505 | 955 | 1535 | 2585 |
| Case 3: engine & aftercooler - separate circuit (kW) | 253 | 530 | 995 | 1600 | 2655 |
| Increase (%), Case 1 to Case 2 | 133% | 35% | 29% | 28% | 18% |
| Increase (%), Case 2 to Case 3 | 11% | 5% | 4% | 4% | 3% |