

Development and Demonstration of a Low Emissions Four-Stroke Outboard Marine Engine Utilizing Catalyst Technology

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ABSTRACT

A conceptual project aimed at understanding the fundamental design considerations concerning the implementation of catalyst systems on outboard marine engines was carried out by Mercury Marine, with the support of the California Air Resources Board. In order to keep a reasonable project scope, only electronic fuel injected four-stroke outboards were considered. While they represent a significant portion of the total number of outboard engines sold in the United States, carbureted four-strokes and direct injected two-strokes pose their own sets of design constraints and were considered to be outside the scope of this study.

Recently, three-way catalyst based exhaust emissions aftertreatment systems have been introduced into series production on sterndrive and inboard marine spark ignition engines in North America. The integration of catalyst systems on outboards is much more challenging than on these other marine propulsion alternatives. Sterndrive and inboard engines are horizontal crankshaft engine derivatives of automotive products. Outboards on the other hand utilize a vertical crankshaft, open cooling systems, and consist almost entirely of components that were specifically designed for a marine outboard engine application.

This report will show how Mercury Marine used state of the art processes and design analysis tools to successfully design a catalyst system for a production based outboard engine targeting combined hydrocarbon and oxides of nitrogen emissions performance equivalent to the sterndrive and inboard standard of 5 grams per kilowatt-hour over the marine engine emissions test cycle. Prototypes of the design were constructed and tested. Results of that testing will be shown that highlight the potential to meet future emissions requirements and some of the challenges that will face commercializing this technology.

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INTRODUCTION

Allowable outboard engine emissions have steadily decreased since the late-1990s. Total hydrocarbons (HC) plus nitrous oxides (NOx) are regulated, along with carbon monoxide (CO). [Table 1](#) shows the California Air Resources Board (CARB) requirements for marine spark ignition (SI) engines based on a rated power of 200 hp (Federal Environmental Protection Agency (EPA) requirements generally follow CARB requirements with implementation lagging by approximately 1-2 years). The reduction in emissions has largely been accomplished by the transition from conventional carbureted and electronic fuel injected (EFI) two-stroke engines to cleaner four-stroke and direct injection two-stroke engines. This shift in technology has enabled three-star emissions compliance on many products. However, in order to reach the next level of emissions reduction, a catalytic converter is required.

Catalytic converters have been introduced on sterndrive and inboard marine SI engines, first in California and presently throughout North America. The program to develop and validate Mercury's current line of catalyzed engine families required tens of thousands of man hours, millions of dollars in capital and expense, and five years to complete. As significant as this program was, integrating a catalyst and closed loop fuel control system on an outboard engine is considerably more difficult. Sterndrive and inboard engines are based on automotive engines that have been specially modified, or "marinized" for marine use. This process usually includes adding a unique fuel system, engine controller, air intake system, accessory drive, and exhaust system. A drive unit, which is the only part of the engine located outside of the boat's hull, is added when the engine is installed in a boat. [Figure 1](#) compares the overall layout of a sterndrive and an outboard engine.

Table 1. CARB Emissions Standards (g/kWh) for Marine SI Engines

OUTBOARD			
Year	Standard	HC+NO _x	CO
Earlier than 2000 ¹	None	~140	~320
2000-2003	One-star	44.9	NR ²
2004-2007	Two-star	36.3	NR
2008-	Three-star	16.3	NR
STERNDRIVE / INBOARD			
2003-2007	Three-star	16.3	NR
2008 (CO in 2010)-	Four-star	5	75 / 25 ³

¹HC+NO_x and CO levels represent emissions from conventional two stroke engines

²NR denotes Not Regulated

³25 g/kWh alternate limit for modes 2-5 only applies to engines over 6.0L in displacement

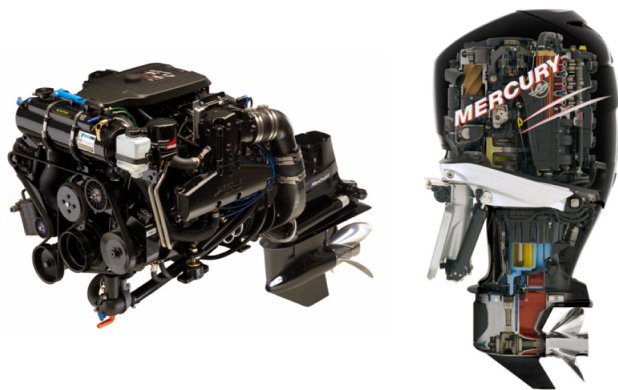


Figure 1. Marine SI Engines - Sterndrive (L) and Outboard (R)

Converting a conventional sterndrive or inboard engine to a catalyzed version typically required a new control system and exhaust manifold(s). In some cases, this meant the addition of an electronically controlled fuel system in place of a carburetor. On engines where EFI was already in place, the engine control unit was upgraded to manage the precise closed loop fueling required to optimize a catalytic converter. In every case, new exhaust manifolds were needed to house the catalyst and oxygen sensors required for closed loop control and onboard diagnostics. The base engine (cylinder block, heads, crankshaft, pistons, water pumps, etc.) was unchanged in this transition. While the overall weight and package volume of the engines was increased, sterndrive and inboard engines usually have less severe weight and packaging constraints than outboards. To add a catalyst exhaust system to an outboard engine would, in most cases, require a new cylinder block and head, exhaust manifold, and adapter plate; along with the controls system changes

mentioned above. This has the potential to greatly increase the size and weight of the engine. While a small change in the weight of a sterndrive or inboard engine may not be critical, it can be much more significant on an outboard engine. This is because outboards start at a much lower weight than their sterndrive and inboard counterparts. Figure 2 shows the specific weight (total engine weight including the drive divided by rated power output) for a selection of outboard and sterndrive engines (for each engine, outboard or sterndrive, where multiple drive configurations are available the lightest version is shown). For example, a 200 hp outboard engine weighs 231 kg where a similar output sterndrive weighs 393 kg. The specific weights of these two engines are 1.16 and 1.79 kg/hp, respectively. For a similar power output, the sterndrive engine is over 50% heavier than the outboard.

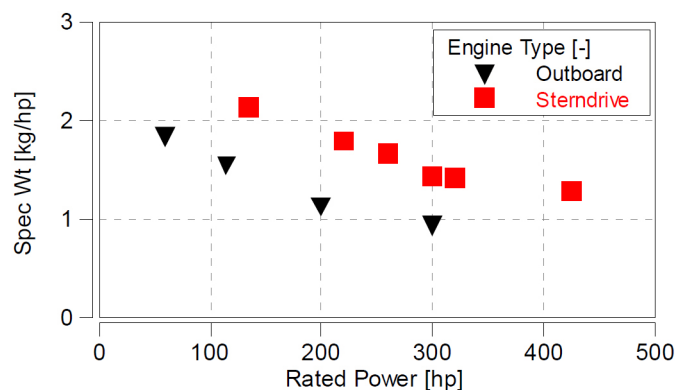


Figure 2. Specific Weights of Sterndrive and Outboard Engines

In addition to being larger and heavier, sterndrive and inboard engines also tend to have lower specific power output than outboard engines. In most cases the addition of a catalyst did not affect their performance. Outboard engines are designed for high power density. Sterndrive and inboard engines are typically rated around 50 horsepower per liter of displacement. Some engines have much higher ratings, but those are typically engines over 500 hp that are used for specialty high performance applications and are produced in very low volumes. Outboard engines, in the range being examined in this study, are often rated between 55 and 70 hp/L, and can be rated as high as 110 hp/L in series production. Engines with higher specific output will likely be more sensitive to an increase in exhaust backpressure, which is an expected outcome of the addition of a catalyst.

Their high specific output and low weight make outboards an attractive marine power choice, especially for smaller boats. Because of their size, outboard powered boats tend to be more sensitive to changes in engine power output and changes to the center of gravity than larger sterndrive or inboard powered boats. Rearward movement of the center of gravity due to a heavier engine can be detrimental to the ability of a boat with a planing hull to accelerate and get on

plane, and can also lead to handling and stability issues (i.e. porpoising) and increased fuel consumption.

Outboard engines, like sterndrives and inboards, use sea water to cool the exhaust gas before it exits the propeller hub. This is done to prevent damage to temperature sensitive components in the exhaust system and gearcase, such as the seals and propeller hub. However, on outboards the water present in the exhaust is much closer to the engine than on a sterndrive. This limits the amount of space available in the exhaust system for placement of the catalyst and oxygen sensors, which must not come into contact with large amounts of water. Due to the packaging and weight constraints discussed earlier, it is not practical to add a large amount of exhaust ducting to the engine to accommodate the catalyst and oxygen sensors.

Outboard engines typically use cast aluminum for all major structural components, including the exhaust passages. To keep the inner walls of the exhaust passages from melting, a cooling water jacket is interposed between the exhaust passage and the outside of the engine. Adding a catalyst to the exhaust system increases the specific size and surface area of the exhaust passage on an outboard more than on a sterndrive or inboard. Consequently, more attention must be paid to proper cooling of the exhaust system to ensure safe surface temperatures. The impact of the additional heat rejected from the exhaust system to the cooling system is significant and must be accounted for.

Because basic structural parts of the engine must change to accommodate the catalyst system, there is the potential for new failure modes to occur, compromising the durability of the engine. The additional loads on the cooling system described above could also create new failures that are not present in a non-catalyzed engine. Any significant impingement of water on to the oxygen sensors or catalyst will result in a failure of the system. This would render the engine non-compliant and, if an OBD system is present, alert the engine operator of a problem. From the operator's perspective, the addition of a catalyst system to an outboard engine should be transparent and not cause any additional requirements for engine service.

This report will show how Mercury Marine addressed these challenges in designing a catalyst system for a currently produced, 1.7L supercharged inline four cylinder engine rated at 200 hp. This report will also show how prototypes of the 200 hp Verado engine were created and the results of various tests run on these engines. Finally, a discussion around the commercial readiness of this technology will be presented including the technical hurdles that must be overcome to bring this technology to production.

PROJECT OVERVIEW

Mercury began this investigation by clearly defining the goals, scope, and timing of the project, including the critical performance attributes and functional requirements of the engine. Some of these were based on the production versions

of the candidate outboard engines, and some were based on the recently completed catalyzed sterndrive and inboard engines that Mercury Marine put into production. A suitable production engine had to be selected for this study. The recently introduced supercharged 200 hp Verado was chosen, in part, because of its design similarity to the larger six cylinder Verado and the naturally aspirated four cylinder version of the engine [1]. A design solution that worked well for the 200 hp Verado should be scalable, both up and down, to these other engines. The 200 hp Verado also presented a more difficult challenge to meet four-star emissions than Mercury's naturally aspirated engines because of its higher starting emissions (the 200 hp Verado is certified at a two-star level), and higher exhaust gas temperatures. Therefore, if a successful solution could be found for the Verado, then applying the design to other engines with less severe requirements should be possible.

Following the engine selection, design concepts were generated and evaluated. The evaluation phase included assessing the potential risks of each concept. This exercise helped to define the test plan for the prototype engines. In parallel, boundary condition data was gathered from production engines. This data included exhaust gas emissions, wide-open throttle performance, and a detailed evaluation of water in the exhaust system.

Following concept selection, detailed designs were created. During this period, tooling was created or modified by Mercury Marine and various suppliers to produce the prototype parts required for the engine build. Once these parts were available, the engines were built using a mix of production and prototype parts.

Four prototype engines were built. They were designated for calibration and emissions testing, cooling system testing, wide-open throttle durability, and customer cycle boat endurance. Each engine was based on a production donor engine, which was torn down and rebuilt with the new catalyst design parts.

Once the prototypes were built, the calibration and cooling system engines were rigged in Mercury Marine's development dynamometer test cells. The wide-open throttle (WOT) durability engine was tested in Mercury Marine's Indoor Test Center (ITC), and the boat endurance engine was rigged on a boat at Mercury Marine's saltwater test facility X-Site in Panama City, Florida. After the completion of testing, the results were analyzed and compiled for this report.

PROJECT DETAILS

BOUNDARY CONDITIONS

Initial boundary condition data from the 200 hp Verado were required to begin designing a catalyst system. The data gathered included exhaust emissions, exhaust temperature, and flow; as well as engine power output and sensitivity to increased backpressure. These tests were run in Mercury Marine's development dynamometer test cells.

In addition to dyno testing, a second round of testing was conducted in a test tank and on various boats to detail the presence of water in the exhaust system. This data was used to determine the appropriate configuration of the exhaust system and acceptable positions for the catalyst and oxygen sensors. For both sets of testing, computer simulation tools were used to corroborate the experimental data to analytical models.

Dyno testing began with emissions mapping tests. Exhaust gas temperature (EGT) measurements were made using thermocouples installed in the exhaust passage. In-cylinder pressure data was recorded with high speed pressure transducers. The engine was fitted with high speed optical rotary encoder, and a combustion analysis system was used to record and analyze the pressure data. An emissions bench measured concentrations of NO, O₂, CO, CO₂, and HC and was used to calculate equivalence ratio (ϕ =stoichiometric/delivered air/fuel ratio). Fuel flow was measured with a high precision fuel balance.

The marine engine emissions test cycle, established by the International Council of Marine Industry Associations (ICOMIA) consists of five steady-state measurements conducted at specific mode points. Each mode point has a weighting factor associated with it, based on an average customer duty cycle. The mode points are defined in Table 2. Mode 1 is run at wide open throttle and rated engine speed. Modes 2, 3, and 4 are run at decreasing speeds and loads that are meant to represent a nominal boat load curve. Mode 5 is run at idle with the gearcase in neutral [2, 3].

Table 2. Marine Emissions E4 Cycle Mode Points

Mode Point	Crankshaft Speed [% of rated]	Propshaft Torque [% of Mode 1]
1	100	100
2	80	71.6
3	60	46.5
4	40	25.3
5	Idle	0

Figures 3 and 4 show the baseline emissions from the 200 hp Verado. Total cycle emissions were 20.23 g/kWh of HC+NOx and 135.5 g/kWh of CO.

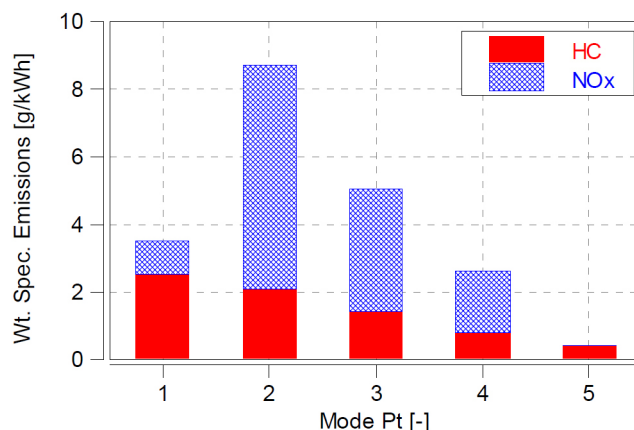


Figure 3. 200 Verado Modal Weighted Specific HC and NOx Emissions

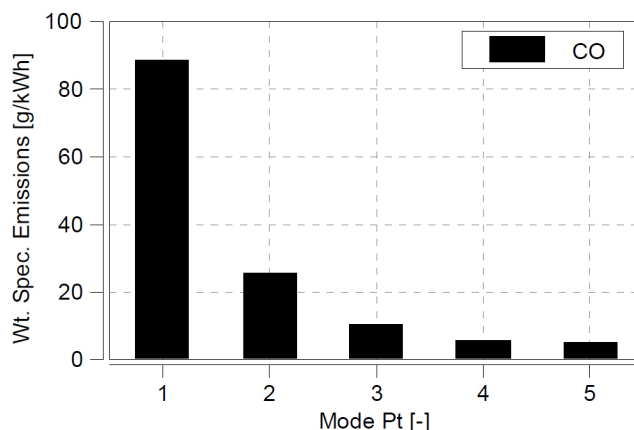


Figure 4. 200 Verado Modal Weighted Specific CO Emissions

At mode 1, the engine's equivalence ratio is calibrated rich of stoichiometric ($\phi > 1$) to control exhaust gas temperature. Adequate margin must be built in at this point to account for production variability in fuel system components, engine aging, and differences in fuels (e.g. ethanol content). The engine examined here does not employ any kind of closed loop fuel control. Therefore, the equivalence ratio at each operating point can change from the target value due to the previously described factors.

At the intermediate mode points (modes 2-4), the fuel calibration is set close to stoichiometric for low fuel consumption. A richer fuel calibration at these points would lower overall HC+NOx emissions to the point where the 200 hp Verado could meet the 3-star emissions standard. However, the 200 hp Verado is calibrated leaner to improve fuel economy. This also yields low HC and CO emissions at the expense of higher NOx emissions, particularly at mode 2. NOx emissions on the 200 hp Verado are proportionally higher than on a naturally aspirated engine due to its use of pressure charging. Mode 5 is calibrated rich for good combustion stability and running quality.

Following the emissions testing exhaust backpressure tests were run. The range of backpressures tested was determined by an initial prediction of exhaust backpressure based on experience with the catalyzed sterndrive and inboard engines. Testing and simulation showed the potential for a 2-5% loss in peak power, depending on the final catalyst and exhaust system configuration.

The next phase of testing focused on quantifying the motion of water in the exhaust system. There are multiple ways that water can enter the exhaust system of an outboard engine while it is running or shut down or transitioning between those states. A test plan was created to address the highest risk failure modes, either by likelihood of occurrence or by the quantity of water brought into the exhaust system. Tests included tank tests, boat testing, and simulation.

Initial tests were run in Mercury Marine's development test tanks. A 200 hp Verado was rigged in a tank and instrumented to measure high speed dynamic exhaust pressure. This data was used to determine instantaneous exhaust mass flow. To do this a pressure transducer in a water cooled adapter was placed in the engine's development oxygen sensor port, and a portable indicating system was used to acquire the signal. Dynamic mass flow in the exhaust was determined using an engine model built using 1D engine modeling software. The model was validated by comparing the simulated pressure to the measured pressure.

The 1D simulation results were fed into a 3D computational fluid dynamic (CFD) model of the exhaust system that included both the exhaust and cooling water flows. This model was used to predict the motion of water from the exhaust cooling sprayer in the exhaust gas stream. *Figure 5* shows the simulation at idle which included the dynamic exhaust flow and exhaust sprayer water flow.

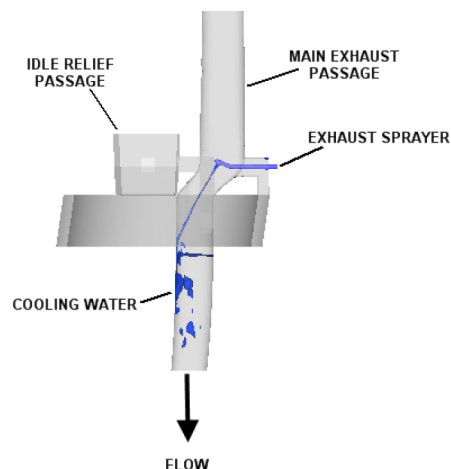


Figure 5. 3D CFD Simulation of the 200 hp Verado Exhaust System

Following the tank testing, extensive boat testing was started. The purpose of these tests was to observe how water entered the exhaust system under different maneuvers and with the engine rigged on various boats. In order to determine

the position of liquid water in the engine, the exhaust system was instrumented. The engine was then rigged on appropriate test boats. A portable data logger was used to record data from each test.

Various tests were run on the engine. An example of these was a test where the boat was accelerated up to a predetermined speed and then quickly slowed by chopping the throttle. The maximum height reached by water as the engine decelerated and settled off plane was recorded for the test. The data showed that an engine rigged on a typical application will routinely have water in the cylinder block portion of the exhaust passage during normal operation. This precludes much of the existing exhaust system from use for the catalyst or oxygen sensors, since repeated exposure to liquid water will certainly damage both the sensors and catalyst.

Figure 6 graphically shows where the running water height is on the 200 hp Verado. The transient water height line shows the height reached by water in the exhaust passage during the test described above. The exhaust system on the 200 hp Verado is typical of other outboard engines. In fact, the same tests conducted on other families of engines have yielded essentially the same results.

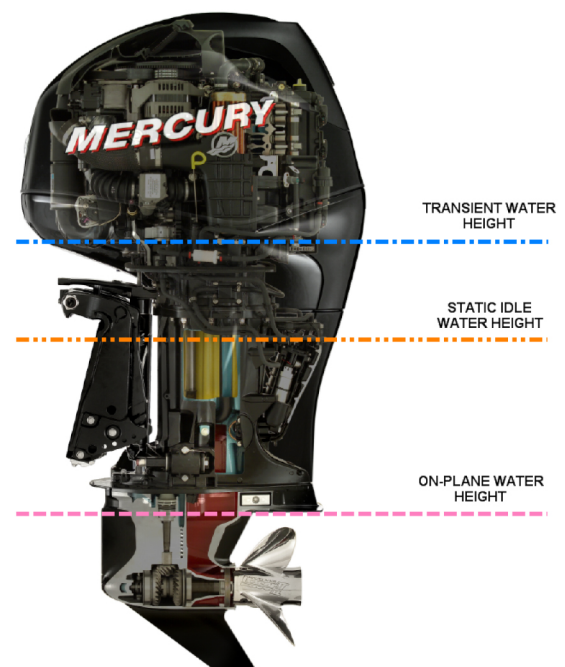


Figure 6. 200 hp Verado Exhaust Water Height

Once baseline testing was complete, additional tests were run with modified exhaust systems. The purpose of those modifications was to reduce the transient water height to a point where sufficient space was available for the placement of the catalyst and oxygen sensors. At the conclusion of this testing, over 100 different tests had been run examining the effects of boat type, engine position, exhaust system configuration, and operating condition.