ICAT Grant # 06-01

Final Report

Development and Demonstration of a Low Emission 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.

The integration of catalyst systems on outboards is much more challenging than on other marine propulsion alternatives. Sterndrive and inboard engines are horizontal crankshaft engine derivatives of an automotive counterpart. Outboards on the other hand utilize a vertical crankshaft, open loop cooling, and consist almost entirely of components that were specifically designed for a marine outboard engine application.

This report will show how Mercury Marine successfully designed a catalyst system targeting combined hydrocarbon and oxides of nitrogen emissions performance equivalent to the sterndrive and inboard standard of 5 grams per kilowatt-hour for two families of outboard engines utilizing state of the art processes and design analysis tools. Prototypes of one of the designs were constructed and tested. Results of that testing will be shown that highlight the potential to meet four-star emissions levels and the challenges that will face commercializing this technology.

EXECUTIVE SUMMARY

Over the last ten years, exhaust emissions standards for outboard engines have become increasingly more stringent. The combined hydrocarbon and oxides of nitrogen (HC+NOx) emissions from modern outboards are more than 80% lower than those of the conventional two-strokes that previously dominated the market. Additionally, carbon monoxide (CO) emissions of the new engines are only half of what they were from conventional two-strokes. For 2008, the California Air Resources Board (CARB) set a new standard for sterndrive and inboard engines of 5 grams per kilowatt-hour (g/kW*hr) HC+NOx, and 75 g/kW*hr CO[*] over the ICOMIA (International Council of Marine Industry Associations) E4 emissions cycle[**]. In order to meet those standards, these engines were equipped with three-way catalytic converters and closed loop fuel control systems.

In 2007, Mercury Marine, the largest recreational marine engine manufacturer in the world, began a program to apply three-way catalytic converters and closed loop fuel control targeting a 5 g/kW*hr HC+NOx emissions level to four-stroke electronic fuel injection (EFI) outboard engines. This program included cost sharing support from the California Air Resources Board Innovative Clean Air Technologies (ICAT) program. Key observations from this project include:

- Catalyst technology has been proven to be a technically feasible and effective method of reducing outboard engine emissions to levels similar to those of catalyzed sterndrive and inboard engines.
- There is a high likelihood that the durability issues that were discovered during this project can be corrected and should not prevent this technology from eventually entering mainstream production.
- The monetary and resource commitments required to convert an outboard engine to catalyst technology are significant and will be a major factor in pacing the transition of the outboard fleet to catalyst technology.

While catalyst technology has been successfully implemented on sterndrive and inboard engines, outboards are significantly more challenging to catalyze. The reasons for this include their highly integrated and custom design, high power density, low weight, small package size requirements, higher thermal loads, and near constant exposure to sea water.

Despite these challenges, Mercury Marine designed prototype exhaust systems for two engines from Mercury Marine's EFI four-stroke product line, the 60 horsepower (hp) EFI and 200 hp Verado incorporating off-the-shelf, ceramic substrate, three-way catalysts. Because of the integrated and custom nature of outboard engines, this required a significant redesign of the entire engine. For each engine, this included changes to the cylinder block, cylinder head, exhaust system, adapter plate, electronic control unit (ECU), electrical system, cowling, shift system, various gaskets, and, of course, the addition of a catalyst and oxygen sensors.

In order to gain an initial indication of the performance and durability of a catalyzed outboard, Mercury Marine created multiple prototypes of a catalyzed 200 hp Verado engine. Though prototypes, these engines were designed to near production standards and were built using many production processes, including the use of Mercury Marine's casting foundry and machining and assembly lines. The prototype engines were put through a series of tests; the

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[*] CO standard takes effect in 2010. Alternately, engines over 6.0 L displacement can certify to 25 g/kW*hr combined ICOMIA modes 2 through 5, excluding mode 1
[**] Emissions test cycle is defined by EPA Part 91 and the California Marine Emissions Test Procedure

results of which indicate both the excellent potential of this technology to reduce outboard emission rates to levels similar to those of catalyzed sterndrive and inboard engines, and the challenges that will need to be overcome to make catalyzed outboards viable products for consumers.

Emissions testing showed that the catalyst, in combination with a properly optimized closed loop fuel system, successfully reduced HC+NOx emissions by 88% compared to the production engine. These initial results, achieved with a fresh catalyst, allow the engine to meet the CARB four-star super ultra low emissions standard for HC+NOx emissions. Examination of the HC and NOx deterioration factors that have been established for Mercury Marine's catalyzed sterndrive and inboard engines suggests that aged HC+NOx emissions would be approximately 4.2 g/kW*hr, resulting in a 16% compliance margin to the four-star limit.

Emissions testing also showed that CO emissions with a fresh catalyst were reduced by 31%. Aged CO emissions (again based on catalyzed sterndrive and inboard deterioration values) would be approximately 112 g/kW*hr for all five modes of the E4 test cycle, and 18 g/kW*hr for modes 2 through 5 of the alternate CO cycle; which would constitute compliance with the alternate CO standard of 25 g/kW*hr should that be available to outboard engines in the future. This reduction in CO emissions is in line with Air Resources Board's stated goal of lowering CO emissions from all internal combustion engines.

Additional testing showed that the changes to the exhaust system, including the addition of the catalyst, caused an increase in exhaust back pressure. Increased back pressure is typically detrimental to engine performance. However, careful design and use of analytical tools, including 1D and 3D flow simulation, reduced the losses to approximately 4% power at rated speed. It is likely that further simulation and development work would yield reduced backpressure, mitigating some of the performance loss reported here.

A three-way catalyst requires a stoichiometric calibration to operate efficiently. Many outboard marine engines employ a rich calibration strategy to reduce engine emissions of NOx, especially at part load cruise points. These engines would show an improvement in fuel economy with the addition of a catalyst system. However, other outboard engines which employ a lean calibration strategy would show a reduction in fuel economy with a stoichiometric calibration. Because of this, it is impossible to draw general conclusions as to the fuel economy impact of adding catalyst technology to outboard engines – each engine must be evaluated individually.

The weight of the engine increased due to the addition of the catalyst system by approximately 9 kg (20 lbs) – a 4% increase in the dry weight of the engine. Through vigilant design efforts, the package size of the engine was not increased significantly. When repackaged, the completed catalyzed engine fit within the current cowling structure (alternately, computer-aided design (CAD) modeling showed that the catalyzed 60 hp EFI would require new cowling).

Although Mercury Marine believes the ICAT test project has successfully demonstrated the feasibility of catalyzing outboard engines, development and endurance testing revealed several design considerations regarding the durability of the prototype engines. Cooling system testing uncovered an issue with the ability of the system to adequately purge air, leading to an overheat condition which damaged the aluminum exhaust manifold casting. Catalyst mounting malfunctions occurred during durability testing. Excessive fuel dilution of the engine oil (which could result in an engine failure) was observed during dyno and boat endurance testing. Also during boat endurance testing, an intermittent malfunction of the post catalyst oxygen sensor (used primarily for diagnostic purposes) occurred, indicating that it likely came into contact with water. There was also evidence of excessive condensation of water in the lubrication and exhaust systems. The tests that exposed these issues are normal validation tests that every outboard at Mercury Marine must pass before it is put into production. Although each of the issues noted here are significant, Mercury Marine is confident that, given adequate development time and resources, solutions could be found that would yield acceptable durability for a production engine.

In order to add a catalyst and closed loop fuel control to an outboard engine, significant changes must be made to it. The scope of these changes is much greater than those required to catalyze sterndrive and inboard engines. Based on the magnitude of these changes, a major redesign, development, and validation program will be required for each engine family. It is reasonable to expect that two to three years will be required per engine family to complete a catalyst conversion program. The investment required to create new or modified tooling for each engine family would be equivalent to approximately 30% of the tooling investment for a completely new engine. This estimate includes some amount of cost sharing of common components across multiple engine platforms. Mercury Marine has estimated that the research and development (R&D) expense to convert an existing engine family over to catalyst technology could be in the range of 50% of the expenses associated with a completely new outboard engine, depending on the specific design of the base engine.

In conclusion, Mercury Marine believes that the results of the ICAT project support the adoptions of catalyst-based standards for outboard engines in the future, so long as reasonable consideration is given to the monetary and time constraints necessary to make this happen. For reference, Mercury Marine currently produces six families of four-stroke EFI engines. Catalyzing all of these engine families would take a significant amount of time to complete, and require very large investments of capital and R&D expenses, as indicated in the previous paragraph. Attempting to convert more than one family per year would be resource intensive for Mercury Marine, especially during the current economic downturn. Mercury Marine estimates that at a rate of one major outboard program per year, it could take up to eight or nine years from the start of the first program to convert the full fleet of Mercury's four-stroke EFI engines over to catalyst technology. As was stated earlier, these estimates do not include the time and resources required to address carbureted four-stroke or direct-injected two-stroke engine families.

1 INTRODUCTION

Allowable outboard engine emissions have steadily decreased since the late-1990s. Table 1 shows the requirements for marine SI engines based on a rated power of 200 hp. The reduction in emissions has largely been accomplished by the transition from conventional carbureted and 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.

OUTBOARD			
Year	**Standard**	**HC+NOx**	**CO**
Earlier than 2000[1]	None	~140	~320
2000-2003	1-star	44.9	NR[2]
2004-2007	2-star	36.3	NR
2008-	3-star	16.3	NR
STERNDRIVE / INBOARD			
2003-2007	3-star	16.3	NR
2008 (CO in 2010)-	4-star	5	75 / 25[3]

Table 1: CARB Emissions Standards (g/kW*hr) for Marine SI Engines

1. HC+NOx and CO levels represent emissions from conventional two stroke engines
2. NR denotes Not Regulated
3. 25 g/kW*hr alternate limit for modes 2-5 only applies to engines over 6.0L in displacement

Catalytic converters have been introduced on sterndrive and inboard marine spark ignition engines in California. The program to develop and validate the three currently available engine families required tens of thousands of man hours, millions of dollars in capital and expense, and three 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.

Converting a conventional sterndrive or inboard engine to a catalyzed version required a new control system and exhaust manifold(s). In some cases, this meant the addition of an electronic fuel injection system (EFI) in place of a carburetor. On engines where EFI was already in place, the engine control unit (ECU) 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 (OBD). The base engine (cylinder block, heads, crankshaft, pistons, water pumps, etc.) was unchanged in this transition. Sterndrive and inboard engines tend to have less severe requirements for package size and weight than outboard engines. Consequently, the addition of the larger catalyst exhaust systems was not as significant an issue as it would be on an outboard. Because of the relative package freedom available on sterndrive and inboard engines, larger catalysts could be fitted to these engines, reducing back pressure and minimizing the effect on performance. Outboards, with their smaller package size requirements and higher specific output, will likely see a greater reduction in performance.

The changes required to add a catalyst and closed loop fueling to an outboard are much more extensive. Most outboard engines have highly integrated exhaust systems in which much of the exhaust path is incorporated into the cylinder head, block, and adapter plate castings. This is done to minimize package volume and reduce the number of bolted joints (each of which is a potential source of water leaks) on the engine. The size and shape of the exhaust passages are typically not conducive to simply "shoving in" a catalyst. Outboard engines, like sterndrives and inboards, use sea water to cool the exhaust gasses before they exit the propeller hub. This is done to prevent damage to temperature sensitive components in the 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.

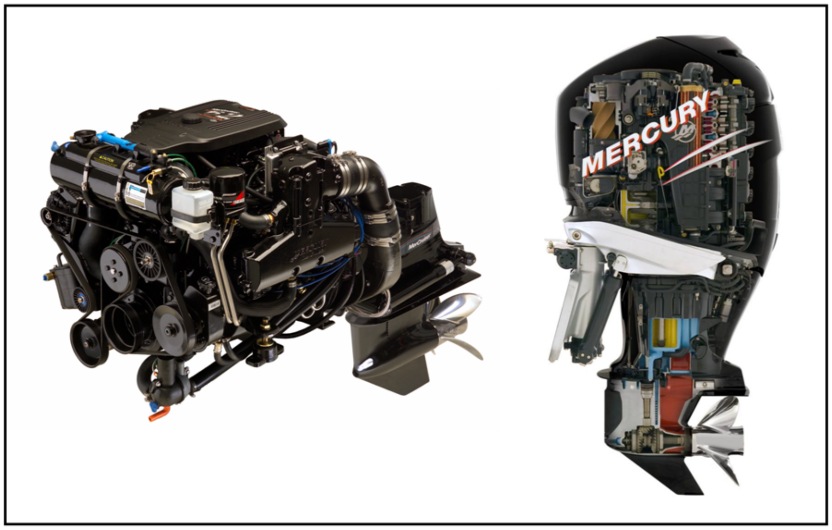

Figure 1: Marine SI Engines - Sterndrive (L) and Outboard (R)

While the outboard engines examined in this study already employ EFI, the current ECUs do not support closed loop fueling. This means that an upgraded ECU and wiring harness are required. Mercury Marine developed a new ECU for catalyzed sterndrive and inboard engines. While this ECU was not designed for outboard use (which typically involves higher vibration loads and higher temperatures), it was applied to the catalyzed outboards examined in this study.

Additional challenges in catalyzing an outboard engine revolve around the high power density of these engines, compared to sterndrive and inboard engines. This, coupled with their low weight, makes 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.

Finally, the addition of a catalyst to an outboard engine has more potential to affect the durability of an outboard engine than that of a sterndrive or inboard engine. This is because basic structural parts of the engine must change to accommodate the catalyst system. As with most first-generation undertakings, this increases the potential for unanticipated malfunctions to occur. Also, additional loads on the cooling system from a catalyzed exhaust system have the potential to create new failures that are not present in a non-catalyzed engine.

This report will show how Mercury Marine addressed these challenges in designing a catalyst system for two engines – a 1.0L inline four cylinder engine rated at 60 hp and a 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 and the resources that would be required to bring this technology to production. This report is the final element of the ICAT grant to demonstrate the viability of a low emissions four-stroke outboard marine engine utilizing catalyst technology.

2 INNOVATIVE TECHNOLOGY

Catalytic converters and closed loop fuel controls have been used for decades in the automotive industry to reduce vehicle emissions of unburned hydrocarbons (HC), oxides of nitrogen (NOx), and carbon monoxide (CO). Over the years, these systems have become increasingly efficient, as ever more stringent regulations have pushed greater reductions in tailpipe emissions. Catalyst technology has also begun to proliferate into other mobile sources, including motorcycles, utility engines, and recently sterndrive and inboard marine engines. The adoption of this technology has enabled sterndrive and inboard engines to achieve CARB four-star super ultra low emissions certification. To achieve this, the aged engine out emissions must be below 5 g/kW*hr HC+NOx and 75 g/kW*hr CO (or, 25 g/kW*hr CO combined modes 2 through 5 for engines over 6.0 L displacement) over the ICOMIA emissions cycle. Although the four-star certification is available to all marine engines, to date only catalyzed sterndrives and inboards have been able to meet the standard.

While introduced on sterndrives and inboards in California, catalyst technology is unproven on outboard engines. Outboards face many additional design constraints, when compared to sterndrive and inboard engines. These additional difficulties stem in part from the highly integrated custom nature of outboard engines. Also challenging is the high power density and low weight expected of an outboard engine. Finally, the outboard exhaust system is much more likely to have a large amount of water present in it than a sterndrive or inboard. Adding a catalyst and closed loop fuel controls to an outboard to reduce its emissions while simultaneously maintaining the positive attributes that make outboards attractive for many marine applications is extremely challenging.

This project was created to examine the application of catalytic converters and closed loop fuel controls to an EFI four-stroke outboard engine. This category of engines covers a wide range of products, extending from 25 to 350 horsepower, engines from three to eight cylinders, displacements from 526 cc to 5.3 L, and naturally aspirated and supercharged. While the largest and most powerful of these resemble automotive engines, the smallest engines more closely resemble simpler utility engines.

Two engines from Mercury Marine's line were selected for this study. The first is a 1.0L inline four cylinder engine rated at 60 hp. This engine forms the basis for a family of engines that include 50 hp and 40 hp versions, as well as carbureted variants. Mercury Marine also produces a three cylinder version of the engine rated at 40 hp (the three and four cylinder versions of the 40 hp engine are used in different applications) which shares a number of common components with the four cylinder engine. The 60 hp EFI model produces 13.26 g/kW*hr of HC+NOx emissions and 151.3 g/kW*hr of CO emissions, and is rated as a three-star engine.

The second engine selected for this study is a 1.7L inline four cylinder supercharged engine rated at 200 hp. This model also represents the highest powered offering in the four cylinder Verado family of engines that also includes 175, 150, and 135 hp versions. The 1.7L architecture is also used for a family of naturally aspirated engines that include 115, 90, and 75 hp models. Major components, including the cylinder head, are shared across the supercharged and naturally aspirated families. The 200 hp Verado model produces 20.23 g/kW*hr of HC+NOx emissions and 135.5 g/kW*hr of CO emissions, and is rated as a two-star engine.

Work was carried out on both engines to design a catalyst system. After the designs were completed, prototypes of the catalyzed 200 hp Verado engine were created. The engines were calibrated, optimizing the closed loop fueling for low emissions. With the catalyst, the 200 hp Verado engine produced 2.41 g/kW*hr of HC+NOx emissions and 93.9 g/kW*hr of CO emissions. This represents an 88% reduction in HC+NOx emissions from the production engine; or, only 15% of the current three-star limit for HC+NOx. With this result, the engine meets the stringent four-star sterndrive and inboard HC+NOx limit. CO emissions were reduced by 31% as compared to the production engine. Nearly 90 grams of the total CO were produced at mode 1. So, while the total CO emissions do not meet the standard 75 g/kW*hr four-star CO target, the engine does meet the alternate 25 g/kW*hr modes 2 through 5 standard available for sterndrive and inboard engines over 6.0 L displacement.

These results represent emissions from an engine with low hours and a relatively fresh catalyst. In order to truly meet the four-star standard, the emissions at the end of the engine's useful life must still be within the four-star limits. While a full aging test was outside the scope of this project, initial estimates of the catalyst aging were made based on aging data from Mercury Marine's catalyzed sterndrive and inboard engines. Using these estimates, the aged HC+NOx emissions of the catalyzed 200 hp Verado would be 4.2 g/kW*hr. Aged CO emissions would be approximately 112 g/kW*hr for all five modes and 18 g/kW*hr for modes 2 through 5.

3 INNOVATIVE CLEAN AIR TECHNOLOGY (ICAT) PROJECT

3.1 BACKGROUND

In 2007, Mercury Marine began a program to apply catalytic converters and closed loop fuel control to outboard engines. Cost sharing support was provided by the California Air Resources Board ICAT program. While this technology has been introduced in California on sterndrive and inboard engines, outboards are significantly more challenging to catalyze. The reasons for this include their highly integrated custom design, high power density, low weight, small package size requirements, and near constant exposure to sea water. Of primary interest is the emissions reduction potential of the technology, the performance impact, the increase in package size and weight, any increase in under cowl temperatures, and any adverse effects on engine reliability or durability.

One of the primary differences between outboard and sterndrive and inboard engines is the custom design and manufacturing of outboard engines. 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. In contrast, an outboard engine is usually a completely unique design, sharing very few components with other engines. Most outboard engines have highly integrated exhaust systems in which much of the exhaust path is incorporated into the cylinder head, block, and adapter plate castings. This is done to minimize package volume and reduce the number of bolted joints on the engine. A CAD model of the 60 hp EFI is shown in figure 2 which illustrates this point.

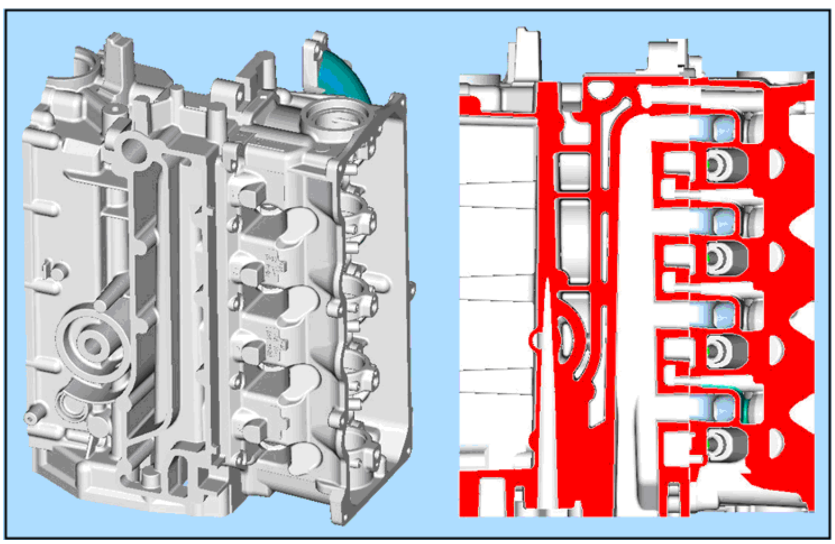

Figure 2: 60 hp EFI Cylinder Block & Head Port Side (L) and Exhaust Cross-Section (R)

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 3 shows the specific weight (total engine weight including the drive divided by 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 was selected). For example, a 200 hp outboard engine weighs 231 kg (509 lbs) where a similar output sterndrive weighs 393 kg (866 lbs). 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.

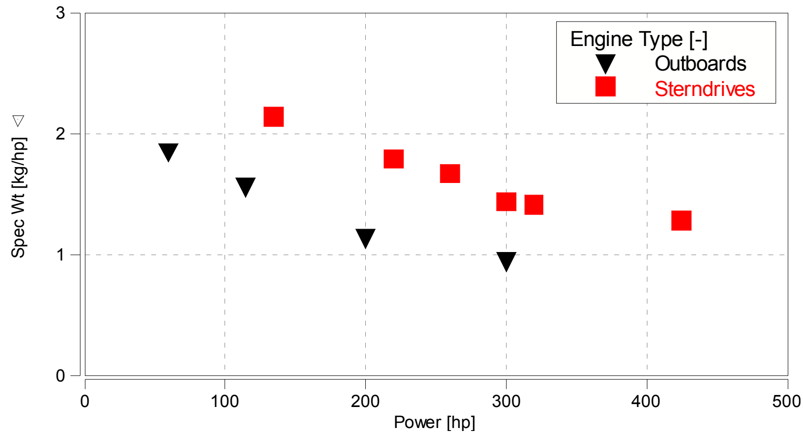

Figure 3: Specific Weights of Sterndrive and Outboard Engines

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 back pressure, which is an expected outcome of the addition of a catalyst. The engine output and weight both combine to affect the performance of the boat.

Outboard engines, like sterndrives and inboards, use sea water to cool the exhaust gasses before they exit the propeller hub. This is done to prevent damage to temperature sensitive components in the 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 passage 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.

3.2 PROGRAM OVERVIEW

Mercury Marine set up the catalyst outboard program much as it would a production engine program. Going through this structured proven process gave the project the highest chance for success. This began with 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. Following this, design concepts were generated and evaluated. The evaluation phase included evaluating 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 both of the candidate 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 for each of the candidate engines. At the completion of the design phase, one engine was selected for prototyping. 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 (WOT) durability, and ICOMIA 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 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.

3.3 BOUNDARY CONDITIONS

Initial boundary condition data from the 60 hp EFI and 200 hp Verado were required to begin designing a catalyst system for each engine. 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 passages. Bulk EGT was measured at the exhaust collector on the 200 hp Verado. Individual thermocouples were placed in each of the exhaust primaries on the 60 hp EFI. In-cylinder pressure data was recorded with high speed pressure transducers. The engines were fitted with high speed optical rotary encoders, and a combustion analysis system was used to record and analyze the pressure data. An emissions bench measured concentrations of NO, O_2, CO, CO_2, and HC and was used to calculate AFR. Fuel flow was measured with a high precision fuel balance.

Table 2 shows the baseline emissions from the 60 hp EFI, and table 3 shows the baseline emissions from the 200 hp Verado.

Mode Pt.	**Speed**	**Torque**	**Lambda**	**EGT**[1]	**Wt. Spec. Emissions [g/kW*hr]**		
[-]	**[rpm]**	**[Nm]**	**[-]**	**[°C]**	**HC**	**NOx**	**CO**
1	5750	76	0.84	726	1.39	1.27	66.5
2	4600	55	0.94	740	1.79	3.89	33.2
3	3450	37	0.90	695	1.43	0.97	30.9
4	2300	20	0.96	629	1.14	0.67	11.1
5	750	0	0.87	395	0.69	0.02	9.6
				Totals	6.44	6.82	151.3

Table 2: 60 hp EFI Baseline Emissions

1. Exhaust gas temperature shown is the average of measurements from all four cylinders

Mode Pt.	**Speed**	**Torque**	**Lambda**	**EGT**	**Wt. Spec. Emissions [g/kW*hr]**		
[-]	**[rpm]**	**[Nm]**	**[-]**	**[°C]**	**HC**	**NOx**	**CO**
1	6100	222	0.87	934	2.49	1.00	88.3
2	4880	159	0.98	887	2.09	6.61	25.8
3	3660	103	0.97	799	1.40	3.62	10.5
4	2440	56	0.95	675	0.80	1.78	5.7
5	650	0	0.81	333	0.43	0.01	5.2
				Totals	7.21	13.02	135.5

Table 3: 200 hp Verado Baseline Emissions

At mode 1, each engine's air/fuel ratio is calibrated rich of stoichiometric ($\lambda<1$) 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 fuel (e.g. ethanol content). The engines discussed here do not employ any kind of closed loop fuel control. Therefore, the air/fuel ratio at each operating point can change from the target value due to the previously described factors.

Engines that employ closed loop fuel control usually use a narrow-range or switching type oxygen sensor in the exhaust to provide the necessary feedback to the ECU. These sensors can only determine whether the supplied air/fuel ratio is rich or lean of stoichiometric (i.e. they cannot be used to determine the actual air/fuel ratio). Typical calibration values used for mode 1 are much richer than stoichiometric – by as much as 20%. At these air/fuel ratios, the oxygen sensor can only indicate that the engine is running rich and cannot be used for fine adjustment of the delivered fuel rate.

At the intermediate mode points (modes 2-4), the air/fuel calibration is set close to stoichiometric for low fuel consumption. The 60 hp EFI employs a richer calibration to keep NOx emissions down and ensure that HC+NOx emissions meet the three-star limit. 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 due to its use of pressure charging. The peak cylinder pressures, and consequently temperatures, are higher on this engine than on a naturally aspirated engine, like the 60 hp EFI, yielding higher NOx emissions. Mode 5 on both engines is calibrated rich for good combustion stability and running quality.

Following the emissions testing exhaust back pressure tests were run. The effect of back pressure was gauged by running a wide-open throttle power test per Mercury Marine's standard procedure. Backpressure on each engine was increased by installing a plate over the gearcase outlet which reduced the effective cross section of the exhaust path. The range of backpressures tested was determined by an initial prediction of exhaust back pressure 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 would be 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 calculated pressure to the measured pressure, as shown in figure 4.

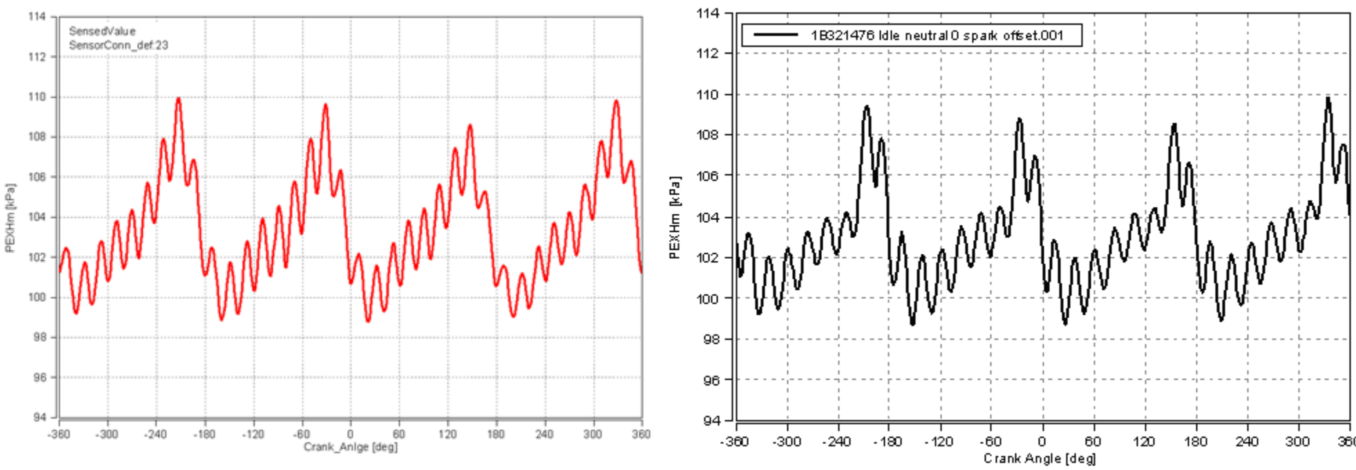

Figure 4: Simulated (L) and Measured (R) Dynamic Exhaust Manifold Pressure at Idle

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 (the sprayer is used to cool the exhaust gas flow before it reaches the gearcase, which contains a number of temperature sensitive components).

Because the exhaust system is completely enclosed, it was difficult to know how accurately the 3D simulation was predicting the water motion. A simplified simulation model was created of a pipe system with a mixture of water and air. A pressure pulse was applied to the model and the motion of water observed. A similar test was carried out in the lab using clear tubing. Video of the lab test was compared to the simulation to judge the efficacy of the model. In general, the predictions were accurate. However, the more complicated engine models did not prove to be very robust, largely due to issues in the simulation software managing two-phase flow.

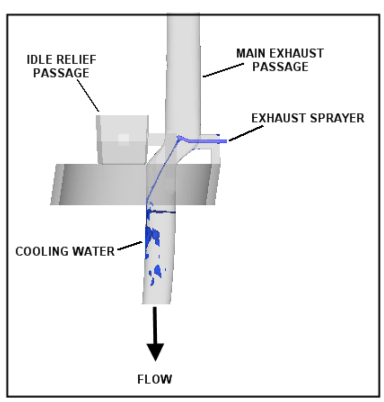

Figure 5: 3D CFD Simulation of the 200 hp Verado Exhaust System

Additional testing was done with a high speed camera placed directly in the exhaust manifold. This required fabricating bosses through the water jacket for the mounting of the camera and light source. The videos generated were used to corroborate the 3D simulation. Figure 6 shows the setup of the 200 hp Verado in the development test tank along with the high speed camera and data acquisition system.

Figure 6: 200 hp Verado with High Speed Camera

Following the tank testing, extensive boat testing was done on both the 60 hp EFI and 200 hp Verado. The purpose of these tests was to see how water entered the exhaust system under different maneuvers and with the engines rigged on various boats. The 200 hp Verado was tested first. Only the most severe tests were then run on the 60 hp EFI engine.

In order to determine the position of liquid water in each engine, the exhaust systems of two test engines were instrumented. The engines were then rigged on appropriate test boats. A portable data logger was used to record data from each test.

Various tests were run on the engines. 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 7 graphically shows where the running water height is on the 200 hp Verado. The transient water height 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 test conducted on the 60 hp EFI (rigged on a 16' aluminum multi-purpose boat) yielded essentially the same result.

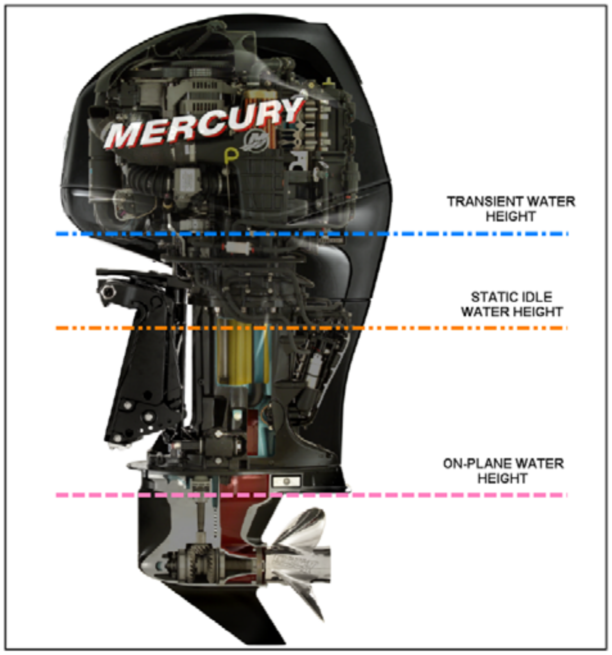

Figure 7: 200 hp Verado Exhaust Water Height

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.

3.4 DESIGN

After adequate boundary condition data had been gathered to define the system requirements, the design phase was started. The first step of this phase was the generation of design concepts. Concepts were identified for each engine, keeping in mind both the likelihood of functional success as well as other attributes critical to a production engine, such as manufacturability, durability, serviceability, and cost of each design. CAD models of each of the chosen concept were created so that the strengths and weaknesses of each design could be evaluated.

Once the concept models were complete, a selection matrix was created to choose the best concept for each engine, based on the functional requirements and attributes of each design. The design that was chosen for each engine represented the best compromise between the requirements for that engine. For both engines the chosen designs required a new cylinder block and cylinder head. Although the new design path required a significant redesign and retooling of the engine, it was determined to be necessary for successful adaptation of the engine to a catalyst exhaust system.

The chosen concept models were then taken and further refined with additional critical details. New exhaust systems were designed for both engines. Particular attention was paid to the internal exhaust passage geometries, to ensure good catalyst utilization. Poor catalyst utilization can lead to high exhaust back pressure (leading to increased power loss), poor emissions reduction, and faster catalyst aging. Consequently, poor catalyst performance may require the addition of more precious metals to meet the emissions target, increasing the system cost.

In order to determine the catalyst utilization, 3D simulation was used. Experience from catalyzing Mercury Marine's sterndrive and inboard engines was used to set the targets for optimum flow uniformity. Multiple iterations of each design were evaluated, and the most favorable selected for the final design. Figure 8 shows an example of the dynamic flow through the exhaust manifold and the instantaneous flow velocity at the face of the catalyst. This analysis was also used to evaluate the placement of the oxygen sensors to ensure good flow distribution across each sensor.

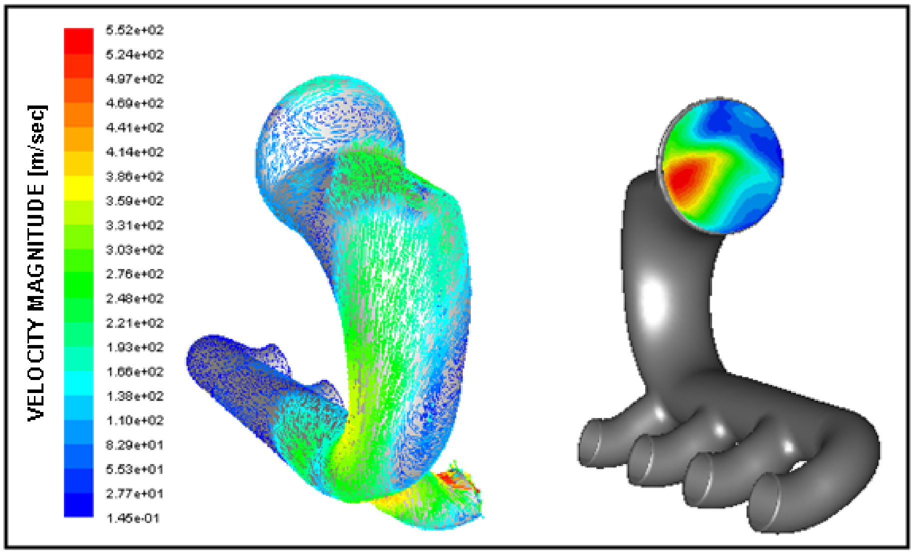

Figure 8: 3D CFD Exhaust Manifold Flow Analysis

Also critical was the design of the water cooling jackets around the exhaust manifolds. The cooling required for the standard exhaust passages was much less than that required for new larger catalyst exhaust systems. This meant that a significantly larger amount of heat energy would have to be absorbed by the cooling system from the exhaust gas. This, in combination with the other changes to the engine, required an extensive redesign of the entire cooling system.

Multiple tools were used to analyze and refine the cooling system before prototypes were built. 3D CFD analysis was again used on the new and revised water passages to optimize coolant flow through each of the components. Thermal inputs were then added to the models to determine coolant temperature, total system heat input, and surface temperature. Comparisons were made between the production versions and the new catalyst versions of each engine to highlight any potential problems. Figure 9 shows a temperature contour of the 60 hp EFI cylinder head at peak power.

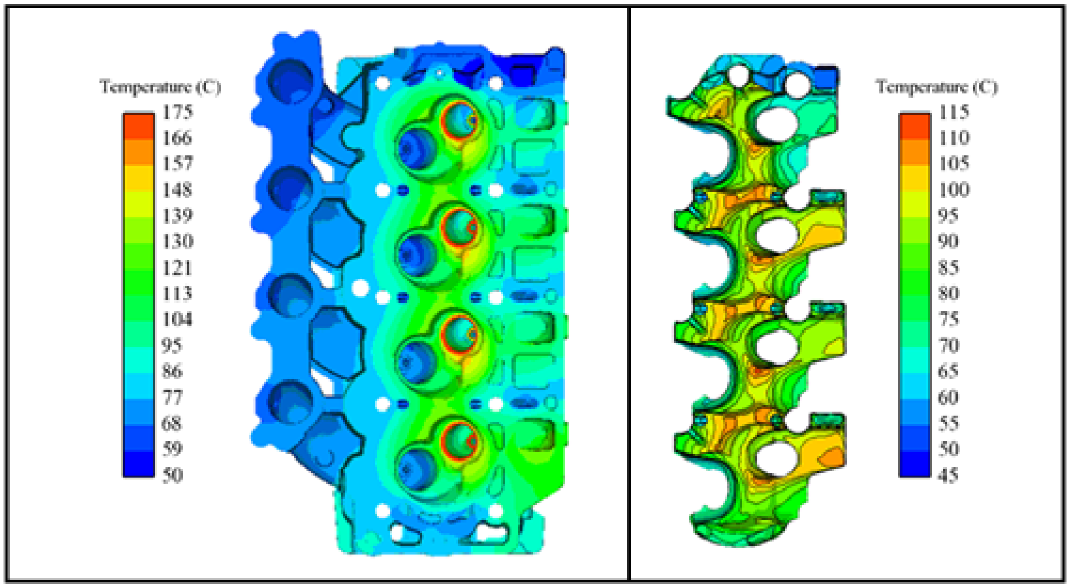

Figure 9: 60 hp EFI Cylinder Head Surface (L) and Water Jacket (R) Thermal Maps

The analysis showed that the catalyst version of the 200 hp Verado rejected approximately 30% more heat energy to the coolant than the stock version. This was largely due to increased surface area between the exhaust passage and cooling water jacket. The increase in surface area was due to the increased passage length required to route the exhaust gasses to the catalyst, and the larger passage diameter required to package the catalyst in the exhaust.

Since the thermostat holds the entire system at a fixed outlet temperature, this leads to a proportional increase in coolant flow rate through the engine. This can cause several problems. First, the water pump must have enough capacity to handle the greater coolant flow demand. Increased coolant flow through the engine can lead to lower temperatures of key components. At very low temperatures, this can promote the formation of condensation in the lubrication system and in the exhaust. Condensation in the lubrication system can cause corrosion on internal components leading to engine damage. Condensation in the exhaust system can enter the cylinders after the engine is shut down, also leading to corrosion. Condensation in the exhaust system has the additional potential to damage the oxygen sensors. In addition to condensation, over cooling of the cylinder liners can lead to high levels of fuel entrainment in the oil. As the temperature of the oil film on the cylinder bores is reduced, its affinity to absorb fuel increases. Dilution of the oil with fuel reduces the oil pressure and viscosity, and can result in engine damage.

In addition to the primary engine cooling circuit, the 200 hp Verado also employs two additional parallel flow cooling circuits for the fuel cooler, and charge air cooler and oil cooler. Increasing the flow through the engine circuit decreases the flow through these other circuits. This can lead to issues with fuel handling (i.e. vapor lock) under hot conditions. This also decreases the effectiveness of the charge air cooler, increasing the charge air temperature and decreasing performance. Increasing the charge air temperature also can advance the onset of combustion knock, which can seriously damage the engine.

Meeting all of the requirements of the cooling system requires a careful balance of coolant flow rates and heat fluxes through each portion of the cooling circuit under various operational and ambient conditions. Achieving this balance requires thorough development testing, and often multiple design iterations. The test results presented later in this report were generated with the first iteration of the cooling system, which did not have the benefit of any development work prior to testing.

In addition to the exhaust flow analysis and cooling system analysis, structural analyses were carried out on the new designs. This analysis took into account the assembly and thermal loads imparted to each component. The major castings, gaskets, and bolts were considered in this analysis. The calculated internal stresses were compared to the material limits for each part to determine safety margin to the fatigue limit. Of particular concern were new or significantly changed parts on the engine. Clamp loads across the bolted joints were also examined to verify gasket sealing performance. A modal analysis was carried out to determine the natural frequencies and mode shapes.   These analyses showed acceptable fatigue performance for all of the components tested, and good clamp load across the new bolted joints.

Once the exhaust passage and water jackets had been sufficiently detailed, the outer surfaces of the parts could be defined. The addition of the catalyst exhaust system to the engine not only required retooling major castings, it also required extensive repackaging of a number of components on both engines. Figure 10 shows the complete assembly of the current production version of the engine. The captions show some of the major packaging changes required to fit the new catalyst exhaust system to the engine.

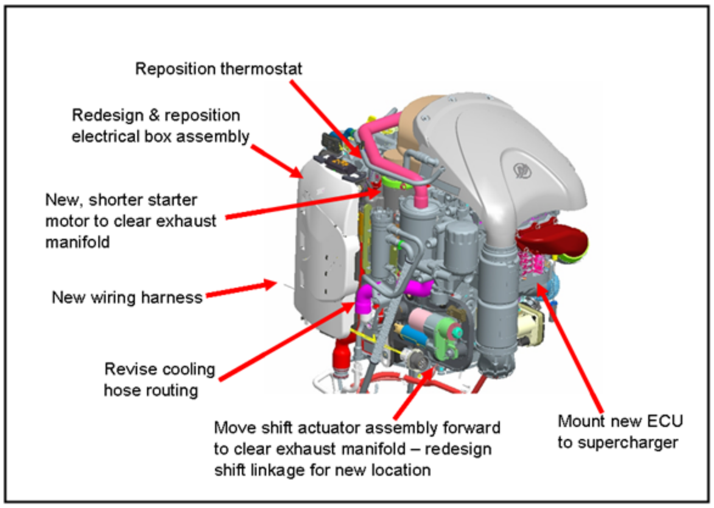

Figure 10: 200 hp Verado Packaging Changes

The 60 hp EFI engine required similar packaging changes, including repositioning the ECU, changing the wiring harness, and repositioning the ignition coils, oil filter, and fuel supply unit. On both engines the outer cowling, which protects the engine from water, manages airflow to the engine, and quiets the noise generated by the engine, was affected by these packaging changes. Mounting points for the cowls moved, and clearances to internal components were reduced or lost all together. This would likely be true of any engine that would undergo such large changes as the outer cowling is typically made as small as possible for a given engine. This is done not only for aesthetic reasons but also for packaging with the boat. Industry standards for the exterior dimensions of an outboard engine ensure that boat builders can choose any make of engine for their product and that they will fit on their product. Exceeding these dimensions can cause issues for any number of boat builders.

The addition of the catalyst and exhaust manifold resulted in an increase in the weight of the engine. The weight of the 200 hp Verado increased by 4%. The 60 hp EFI weight increase was similar to slightly lower. As has been discussed, this can have a detrimental effect on boat performance. Increasing the weight of the engine can also require a redesign of the engine mounting system, which is specifically designed for a given engine weight. Without increasing the load capacity of the system, a serious failure could occur due to insufficient mount strength.

Each of the major components that were changed during this study would need to be retooled for production. This would mean creating all new tooling, as there would be virtually no opportunity to back fit the new catalyst designed parts to current technology engines. Figure 11 shows that the investment required to create new tooling for these components would be equivalent to approximately 30% of the tooling investment for a completely new engine.

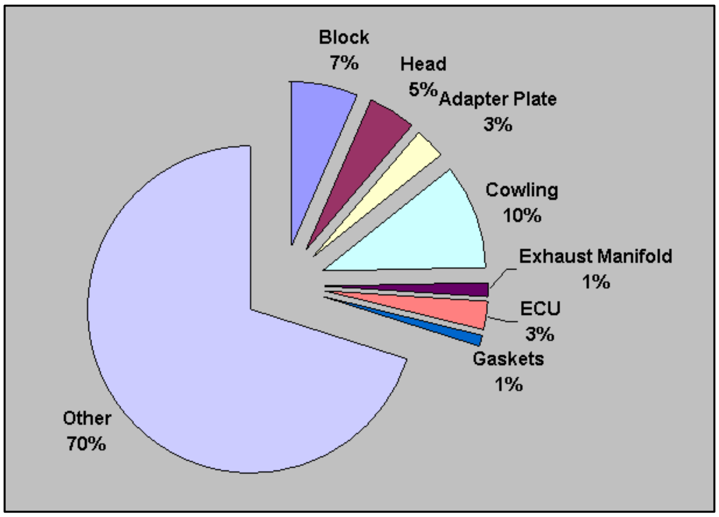

Figure 11: New Outboard Engine Capital Tooling Costs

3.5 ENGINE BUILD

In order to gain an initial indication of the performance and durability of a catalyzed outboard, Mercury Marine created multiple prototypes of a catalyzed 200 hp Verado engine. The 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. 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 because of its higher starting emissions. The 200 hp Verado produced higher exhaust gas temperatures, due to its supercharged nature, than the 60 hp EFI. 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.

Creating the prototype engines required a long list of new parts. The most significant, from the perspectives of tooling lead time, design effort, and expense were the cylinder block, cylinder head, exhaust manifold, catalyst housing, and catalyst assembly. In addition to these, other new parts needed to be designed and fabricated including gaskets, fasteners, brackets, the wiring harness, and starter motor. Table 4 is a summary list of the new and modified parts used on the prototype catalyzed 200 hp Verado engines.

Base Engine	Peripherals	Midsection & Cowls
Cylinder Block	Electrical plate assy	Adaptor plate
Cylinder Head	Wiring harness	Stud
Exhaust manifold assy	ECU	Nut
Exhaust manifold	ECU brackets	Exhaust sprayer
Catalyst Housing	Starter	Sprayer hose
Flange gasket	Starter bottom mount cap	Adaptor plate gasket
Air bleed fitting	Starter mount screws	Exhaust tube
Water temp sensor	FSM vent hose assy	Idle relief fitting
Fasteners	Oxygen Sensors	Idle relief hose
O-ring - upper	IOM dump hose fitting	Stbd bottom cowl
O-ring - lower	Shift actuator assy	
Catalyst assy	Shift bracket	
Fasteners (man. to head)	Bell crank	
Head gasket	Rail slide	
Exhaust manifold gasket	Shift link	
Flywheel (58x)	Rail	

Table 4: Catalyzed 200 hp Verado Special Parts List

The only way to create the complicated prototype cylinder head and block castings was to utilize Mercury Marine's production casting and machining facilities. Close integration between the Product Development and Manufacturing divisions of Mercury Marine made this possible.

The cylinder block castings were created by modifying lost foam tooling that was used to create the first prototype four cylinder Verado engines. The cylinder block foam assembly consists of five segments. All five segments needed some level of modification. The major changes consisted of removing the production exhaust collector and exhaust passage features, and replacing those with part of the new catalyst exhaust system. Along with the mold tools, new assembly tools and gluing fixtures had to be created. The tooling modifications, foam pattern molding, and assembly were carried out by Mercury Marine's production suppliers.

The finished foam patterns were then sent to Mercury Marine's lost foam casting facility. There, the blocks were cast, heat treated, qualified, and fitted with the cylinder liners. Following that, the blocks were moved to Mercury's machining and assembly plant for painting and machining. Production machining was able to add most of the features to the block, with the exception of the new exhaust system features. Those features were added in Mercury Marine's in-house Engineering Model Shop. After a final inspection, the blocks were sent to the Engineering Lab for leak check and assembly.

The cylinder head castings were also created by modifying lost foam tooling that was used to create the first prototype four cylinder Verado engines. Like the block, the head consists of five segments, each of which had to be modified for this project. The tooling modifications, foam pattern molding, and assembly were carried out by the same suppliers that worked on the cylinder blocks.

Mercury Marine's lost foam casting facility also cast these parts. Like the blocks, the heads were cast, heat treated, painted, and qualified in the production facility before being transferred to Mercury's machining and assembly plant. There the heads were machined and the valve seats and guides were assembled to the head. The heads were then sent to the Model Shop for final machining of the catalyst system specific features. Following the Model Shop, the heads were sent to the Engineering Lab for leak check and then back to Production for valvetrain assembly. Following valvetrain installation, the heads were returned to Engineering for the build.

The exhaust manifolds were made as sand castings. The castings were fairly complicated, consisting of six cores (two for the exhaust passages and four for the water jacket). After casting and heat treat the parts were shipped to Mercury Marine and machined in the Model Shop. Following machining, the parts were leak checked in the Engineering Lab. After successful leak check, the parts were sent to Production for painting and then returned to the Engineering Lab for the build.

The catalyst housings were also made as sand castings. The housing was a much simpler design, though it did require some iteration to get good concentricity between the inner bore, water jacket, and outer wall. The parts were cast and heat treated before being shipped to Mercury Marine. The parts were machined in the Model Shop and the leak checked in the Engineering Lab. Following leak check, the parts were sent back to Production for painting and then returned to the Engineering Lab for the build.

The catalyst assembly consisted of a ceramic catalyst substrate surrounded by a mat and a stainless steel mantle. A commercially available 400 cells per square inch (cpsi), 6.5 mil wall substrate was chosen for this engine. The mat was also a commercially available product from a well known automotive supplier. The mantle was similar in design to an automotive design, with the exception of a flange at one end for securing the catalyst assembly within the outboard exhaust system.

This design was deemed to be the lowest cost option for the catalytic converter. Alternatively, a metallic substrate, similar to those used on Mercury Marine's catalyzed sterndrive and inboard engines could have been used. The metallic substrate would have offered lower pressure drop (i.e. less back pressure) and a higher surface area than the ceramic design, but at a higher unit cost.

The washcoat for the catalysts was based on a production washcoat used on Mercury Marine's sterndrive and inboard engines. This washcoat is also a commercially available automotive washcoat technology. However, the precious metal loading of the catalysts tested here was significantly higher than those typically used in automotive applications. This was done to minimize the required substrate volume, yielding a smaller overall package size.

Three new gaskets were required for the catalyzed 200 hp Verado engines. These were all designed as coated single layer beaded steel gaskets. The gaskets were laser cut, and prototype tools were created for the bead stamping.

The exhaust passage in the adapter plate had to be modified to match with the changes to the bottom of the block. The Model Shop accomplished these changes by cutting the outer side of the exhaust passage out of the adaptor plate. New inner and outer walls were fabricated and welded into the plates to match the new bottom profile of the cylinder block.

A new starter motor was selected for the catalyzed 200 hp Verado. The standard starter was abandoned due to packaging conflicts. The new starter was significantly shorter than the stock part and required a different mounting arrangement than the production engine. This required the fabrication of new upper and lower end caps for the starter.

The new catalyst exhaust system interfered with the stock location of the shift actuator assembly. Therefore, a new assembly was designed to move it forward and away from the exhaust. This required a new bracket, which utilized the existing mounting bosses on the crankcase and one new boss on the block. A modified bell crank and shift linkage were created to match the kinematic relationship between the shift shaft and actuator to the production engine. The rail and slider had to be modified for mount bolt access and clearance. All of these components were fabricated in the Model Shop.

Finally, a different ECU was required for the catalyzed 200 hp Verado. The stock ECU did not have the capability to run with closed loop fuel control. A new ECU, the PCM09, was developed for Mercury Marine's catalyzed sterndrive and inboard engines and was used for the 200 hp Verado prototypes. The PCM09 was physically larger than the stock part, so a new mounting location had to be devised. In addition to the new ECU, a brand new software platform was developed by Mercury Marine to run catalyzed engines. Several changes were required in order to apply this software to the 200 hp Verado. The primary change was the addition of the boost control strategy. Dyno and boat testing was conducted on a production 200 hp Verado prior to the prototype build to validate the new software and ECU.

Once all of the prototype parts had been gathered, four production donor engines were acquired for the build. The production engines were torn down, and then rebuilt with the new catalyzed version parts. Each build engine had unique instrumentation, based on its intended testing use. The first engine built was used for calibration and emissions testing. Special instrumentation on this engine included exhaust gas temperatures, catalyst bed temperatures, and cylinder pressure transducers.

The second engine built was the cooling system development engine. This engine included numerous temperature measurements of the intake air, cooling water, metal, exhaust gas, and oil. The location of some of these measurements was made common with those taken on production engines so that a good comparison could be made between the two. Flow meters were also installed to measure water flow rate through the different cooling circuits on the engine.

The final two engines built were the durability test engines. Both engines had minimal instrumentation. Data from the boat endurance engine was recorded with an ECU data logger. Mercury Marine's Indoor Test Center (ITC) was used to test the wide open throttle endurance engine. The ITC data acquisition system monitored ECU channels, as well as selected measurements used to automatically shut down the engine based on signs of trouble (e.g. low oil pressure). The ITC engine was the only one built with a 25" midsection (midsection length is roughly equivalent to the distance between the bottom of the cylinder block and the running on-plane water line – see figure 7). The other engines were built with 20" midsections. Engines with 25" midsections are typically tested in Mercury Marine's ITC to minimize cavitation effects. 20" is the shortest midsection length available for most outboard engines over 40 hp. The boat endurance engine was built as a 20" engine to provide a worst case application, with regard to water intrusion through the exhaust system affecting the oxygen sensors and catalyst.

3.6 TESTING

For calibration, performance, and emissions testing, the first test engine was rigged in Dyno Cell 1. An emissions probe was installed in the exhaust manifold upstream of the catalyst, and a second probe was installed in the block downstream of the catalyst. Each probe was connected to an emissions bench measuring CO, carbon dioxide (CO_2), oxygen (O_2), HC, and NOx. Fuel flow was measured using a fuel balance. Cylinder pressure indicating equipment was also fitted to the engine. Pressure transducers were installed, and a combustion analysis system was used to record and analyze the cylinder pressure measurements. Thermocouples were installed in the catalyst at 30, 60, 90, and 120 mm from the inlet face. Exhaust back pressure was measured upstream of the catalyst. Wide open throttle tests were run with 87 octane regular fuel per Mercury Marine's standard procedure. All emissions tests were run using EEE fuel (EPA Tier II emissions reference grade fuel) per the standard ICOMIA procedure.

Results of the wide open throttle power test are shown in figure 12. Torque on the catalyzed engine was lower above 3,500 rpm, and power at rated speed was reduced by 8 hp (4%). The peak power point moved out to 6,400 rpm from 6,100 rpm. Peak power was lower than the production baseline by about 5 hp.

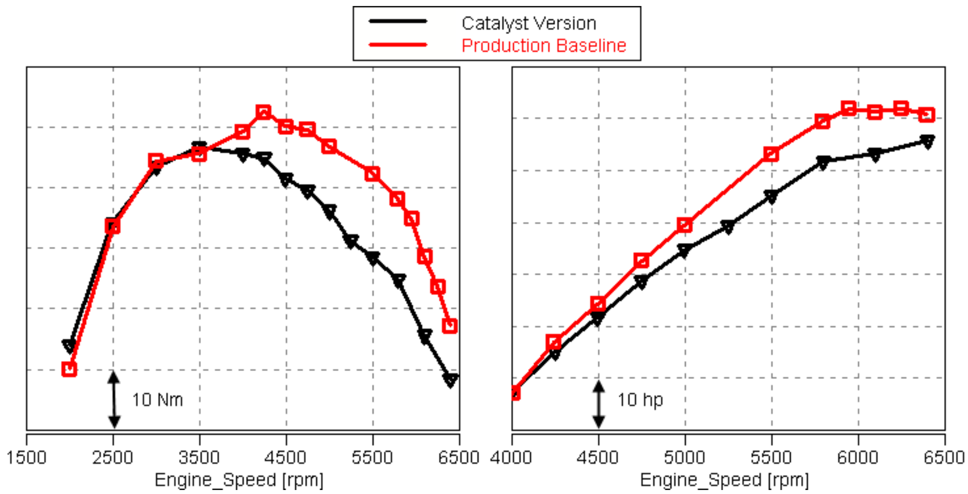

Figure 12: Catalyzed 200 hp Verado Wide Open Throttle Torque (L) & Power (R)

Reduced air flow due to higher back pressure at the exhaust valves accounted for the drop in power with the catalyst engine. Peak exhaust back pressure increased by approximately 30 kPa due to the addition of the catalyst. Testing indicated additional flow losses in the exhaust primaries upstream of the catalyst, compared to the production engine. The combination of these effects contributed to the performance loss shown above.

Following the baseline wide-open throttle testing, detailed calibration work was carried out, initially focusing on the ICOMIA mode points, and then spreading out to the entire engine operating map. Calibration parameters including target air/fuel ratio and air/fuel ratio perturbation frequency and amplitude were optimized at each point for best emissions.

At the intermediate mode points (modes 2 through 4), there was considerable freedom in setting the air/fuel ratio. Catalyst bed temperature was highest at mode 2, but still within acceptable limits. Air/fuel ratios were set for the best conversion of both HC+NOx and CO. Figure 13 shows the weighted specific emissions at modes 2 through 4 versus air/fuel ratio.

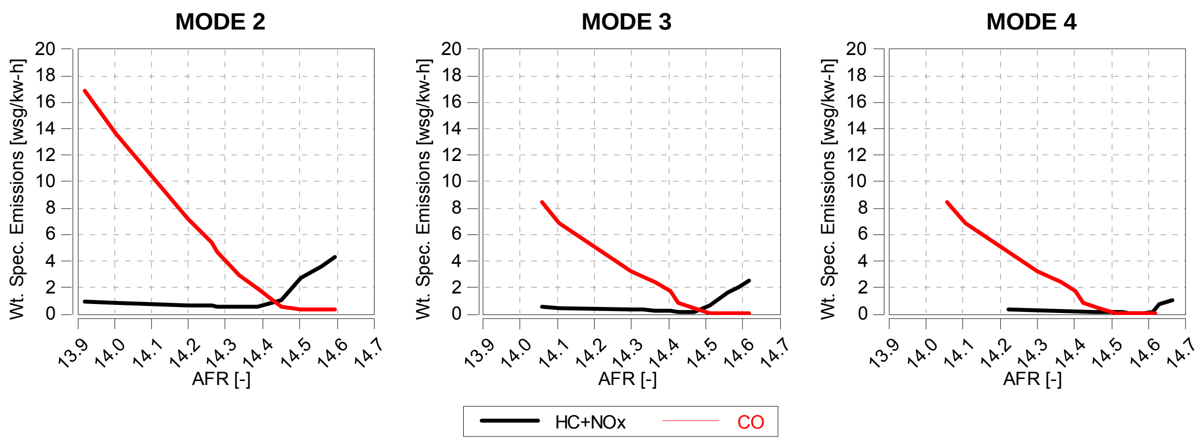

Figure 13: Emissions versus Air/Fuel Ratio, Modes 2-4

At mode 5 (idle out of gear), the target air/fuel ratio was set close to stoichiometric. However, because of the large water jacketed surface area of the exhaust manifold, the catalyst inlet exhaust gas temperature was too low to sustain significant catalytic conversion. The manifold surface area was maximized to cool the exhaust gas to an acceptable level at modes 1 and 2. This came at the expense of low inlet temperature at idle. Figure 14 shows the catalyst response as the engine was brought to idle from mode 4. Inlet gas temperature (TECat_I) stabilized at about 170°C. Catalyst mid-bed temperatures, measured at 30, 60, 90, and 120 mm from the inlet face (TECat030, TECat060, TECat090, and TECat120 respectively) stabilized at approximately the same temperature. The graph shows that the catalyst HC conversion efficiency drops from over 95% to 50% in 160 seconds. HC conversion efficiency stabilizes in the 5-10% range approximately 210 seconds after the transition to mode 5. Idle HC emissions are 0.03 g/kW*hr initially, increasing to 0.35 g/kW*hr after the catalyst has cooled.

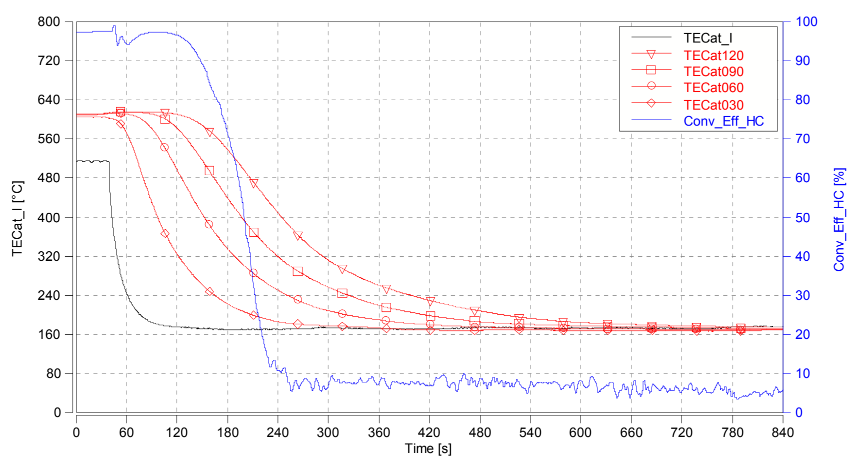

Figure 14: Catalyst Response, Mode 4 to Mode 5 Load Step

At higher speeds and loads approaching mode 1, the target air/fuel ratio had to be set rich of stoichiometric to prevent excessive temperatures at the exhaust valves (typical of nearly all other marine engines) and in the catalyst. The exhaust valve temperature limit for this engine had been established during the development of the production engine using measured temperatures in the cylinder head and valvetrain. The catalyst temperature limit was based on supplier recommendations. The catalyst temperature was measured using the previously described mid-bed thermocouples.

Because the air/fuel ratio at mode 1 was set rich of stoichiometric, the effectiveness of the catalyst, especially in the oxidation of CO, was limited (although NOx reduction and HC oxidation were still fairly effective). Therefore, the air/fuel ratio at mode 1 was set as lean as possible to reduce engine out CO emissions without exceeding the temperature limit of the catalyst. Because of its high specific output, the 200 hp Verado exhaust gas temperatures are higher than those of most sterndrive and inboard engines. Combined with the very compact design of the exhaust manifold, this led to higher catalyst inlet temperatures at mode 1 than are seen on catalyzed sterndrive and inboard engines. Consequently, it was not possible to run the engine lean enough to meet the 75 g/kW*hr five mode point CO target.

Table 5 shows the optimized emissions results from the catalyzed 200 hp Verado, including the percent reduction from the baseline levels. Overall HC+NOx emissions with a fresh catalyst were 2.41 g/kW*hr, compared with 20.23 g/kW*hr for the production baseline. The catalyzed engine shows an 88% reduction in HC+NOx emission – more than 50% below the super ultra low four-star standard. CO emissions were reduced by 31%, down to 93.9 g/kW*hr from 135.5 g/kW*hr. Clearly, this result does not meet the 75 g/kW*hr CO target established for sterndrive and inboard engines. However, a closer examination shows that nearly all of the CO emissions come from mode 1. Only 6.4 g/kW*hr were produced at the remaining mode points. Therefore, the engine would meet the alternate 25 g/kW*hr standard for modes 2 through 5 that is currently available for sterndrive and inboard engines over 6.0 L in displacement.

	Wt. Spec. Emissions [g/kW*hr]			**Reduction from Baseline [%]**		
Mode Pt.	**HC**	**NOx**	**CO**	**HC**	**NOx**	**CO**
1	1.18	0.14	87.5	53	86	1
2	0.31	0.23	3.8	85	97	85
3	0.09	0.07	0.5	94	98	95
4	0.02	0.01	0.1	98	99	98
5	0.35	0.01	2.0	19	0	62
Totals	1.95	0.46	93.9	73	96	31

Table 5: Catalyzed 200 hp Verado Emissions Results

Catalyst aging was estimated using data from Mercury Marine's catalyzed sterndrive and inboard engines. The deterioration factors (DF) for these engines were scaled to account for the difference in the useful life requirement between sterndrive and inboard engines and outboards, and are summarized in table 6.

	Scaled Deterioration Factor (multiplier)			
Engine	**HC**	**NOx**	**CO (5 Mode)**	**CO (Modes 2-5)**
3.0L	1.22	3.54	1.08	1.41
5.0L	1.26	1.09	1.13	1.64
5.7L	1.23	3.14	1.19	1.89
6.2L	1.15	1.90	1.23	1.97
8.1L	1.84	2.31	1.36	6.82
8.1L HO	1.39	8.63	1.15	3.29
Average	1.35	3.43	1.19	2.84

Table 6: Scaled Deterioration Factors Based on Catalyzed Sterndrive & Inboard Engines

Based on this analysis, aged HC+NOx emissions for the catalyzed 200 hp Verado would be approximately 4.2 g/kW*hr. Aged CO emissions would be 112 g/kW*hr for all five modes and 18 g/kW*hr for modes 2 through 5. Aged emissions results relative to the four-star limits are summarized in table 7.

	Wt. Spec. Emissions [g/kW*hr]		**Aged Margin to 4-Star Limit [%]**
	Fresh	**Aged**	
HC+NOx	2.41	4.2	16
CO (5 Mode)	93.9	112	-49
CO (Modes 2-5)	6.4	18	28

Table 7: Catalyzed 200 hp Verado Aged Emissions Projections

After dyno testing, the first engine was removed from the dyno and rigged on a boat for drivability calibration work. Drivability calibration focused on a number of parameters, including improving throttle feel and transient fueling. This work was done so that a drivable calibration would be ready for the boat endurance testing scheduled to occur later in the project.

Dyno testing continued with the cooling system development engine. This engine was rigged in another cell, which had expanded capabilities for hot and cold ambient conditions. Initial testing focused on determining the proper thermostat temperature for the catalyst 200 hp Verado engines. Normally, this engine used a 70°C thermostat. However, the catalyst engines showed severe thermostat cycling issues with this thermostat, which forced a change to a 60°C thermostat.

After this change, steady state testing was conducted at nominal, hot, and cold ambient conditions. In general, temperatures in the catalyst engine cooling system were slightly lower than those of the production baseline. This was due to the approximately 30% higher rate of water flow through the engine because of additional heat rejection from the exhaust. Some thermostat cycling was still observed with the catalyst engine and 60°C thermostat. Also, intake air temperature after the charge air cooler was higher on the catalyst engine than the production engine. This was due to reduced water flow through the charge air cooler leading to lower efficiency of the heat exchanger. Water flow through the charge air cooler circuit was reduced because of the higher flow requirement of the engine cooling circuit.

Following the steady state testing, transient tests of the engine were run to judge the ability of the cooling system to handle rapid changes in engine operating condition. Multiple versions of the cooling system were tested, with changes designed to improve either steady state or transient performance. Often, the requirements of these two tests were contradictory. Changes that improved steady state performance often hurt transient response. This issue was exemplified during one transient test when the cooling system was unable to purge a pocket of air in a portion of the exhaust manifold cooling jacket. The lack of cooling water caused a local hot spot to form on the inner wall of the exhaust passage which eventually melted and created a hole in the manifold. After the test, the manifold was removed and the outer wall cut away to better observe the failure. Figure 15 shows the failed manifold.

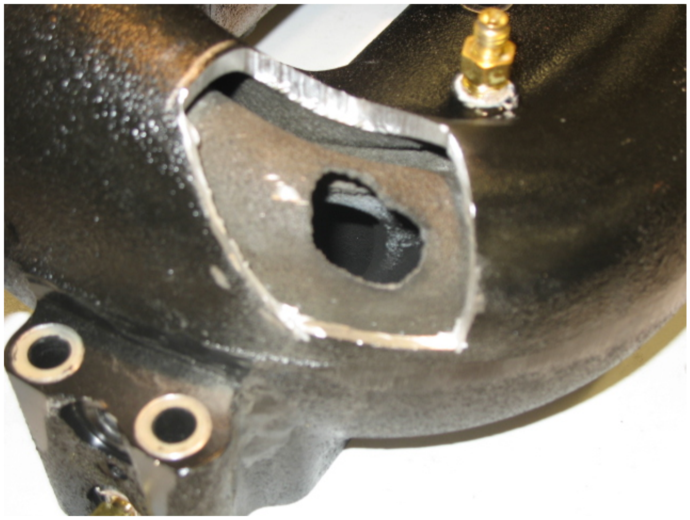

Figure 15: Exhaust Manifold Failure

The failed manifold was replaced, and additional tests run on the engine. These focused on evaluating oil dilution and condensation. A standard oil dilution test was run on the engine, using a reference fuel. Following the test, samples of the engine oil were measured to determine the amount of fuel in the oil. The tests showed that the catalyst engine had significantly higher amounts of fuel in the oil than production engines run on the same test (additional detail to follow).

A standard condensation test was run on the engine to look for signs of water condensation in the lubrication and exhaust system. The test involves running the engine at idle for a prescribed amount of time on cold water. After the test was complete, the engine was partially disassembled and examined. Figure 16 shows the cylinder head (left and center) and catalyst housing (right) after the test. The white deposits shown in the cylinder head under the exhaust cam (left) and between the spark plug towers (center) are water/oil emulsion that formed when the oil in the overhead mixed with condensed water. The catalyst housing (right) shows condensed water droplets along the entire length of the exhaust passage, including around the post-catalyst oxygen sensor (circled). As was discussed earlier, condensation in the lubrication side of the engine can lead to corrosion of internal components. In this case, a number of valvetrain components would be at risk. Additionally, the presence of liquid water in the exhaust system has the potential to cause corrosion issues if it gets back into the engine. On an engine with closed loop fuel control, the liquid water could also lead to an oxygen sensor failure.

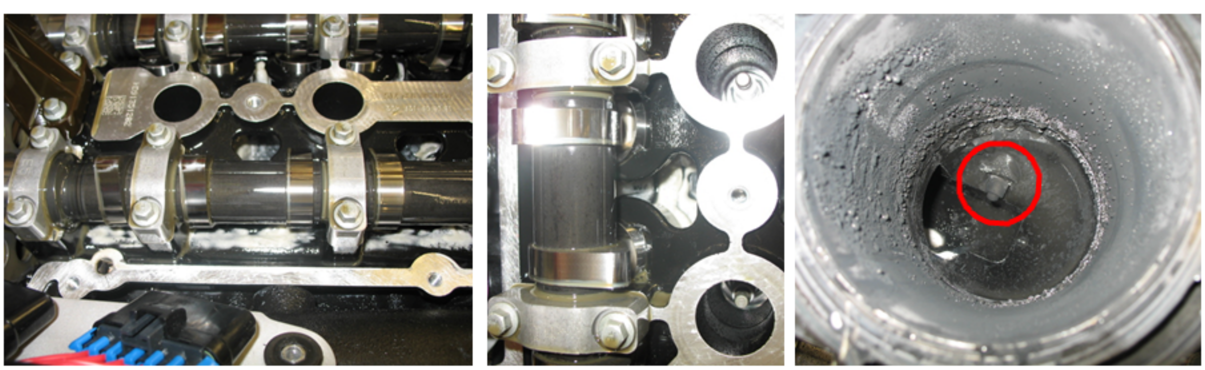

Figure 16: Condensation Test Results

The two remaining engines were used for initial durability testing. Durability testing took place in the Mercury Marine Indoor Test Center and at Mercury Marine's X-Site saltwater boat test facility in Panama City, Florida. Both engines were run on a dyno to break the engines in and establish a baseline before endurance testing. Testing in the ITC involved 100 hours of continuous wide open throttle operation. The boat endurance engine ran 100 hours of ICOMIA cycle testing.

After dyno testing, the WOT test engine was rigged in the ITC. A data acquisition system was attached to the engine, and it was set up to run 6,100 rpm – i.e. rated speed for the 200 hp Verado. The engine was then run for 100 hours, with periodic breaks for scheduled maintenance and inspections. The engine was also shut down occasionally for minor testing issues. For example, at one point during the test a loose connection on the prototype wiring harness caused erratic battery voltage, shutting down the engine.

After the ITC test was complete, the engine was returned to the dyno for an end of test check. Testing showed that the engine was in a good state of health. After dyno testing, the exhaust manifold was removed to inspect the catalyst. At this point, a failure of the catalyst mounting structure was discovered. During the test, the substrate had slid down and partially out of the mantle, eventually coming to rest on an internal wall in the exhaust passage (see figure 17). Analysis showed that the mounting mat between the substrate and mantle had failed to exert enough radial pressure to hold the substrate in place. A design change to the mat and potentially the mantle would be required to address this issue.

Figure 17: Failed Catalyst From WOT Test

As with the WOT engine, the boat endurance engine was baseline tested on the dyno before being sent out for test. The engine was rigged on a specialized endurance testing boat – in this case, a 22' Velocity. When set up correctly, this boat was capable of reaching 60 mph at wide open throttle.

Figure 18: Catalyst 200 hp Verado on Boat Endurance

The boat was then run through a specified cycle that approximates the ICOMIA cycle. The test cycle also included a number of shift events and shut-down and start-up sequences, to simulate real world conditions. The boat was run in a range of sea conditions. The boat was also towed and acted as a tow boat, to add to the number of real world situations that boats can experience. Figure 19 shows the scatter of speed and load points logged during endurance testing, along with the ICOMIA mode points.

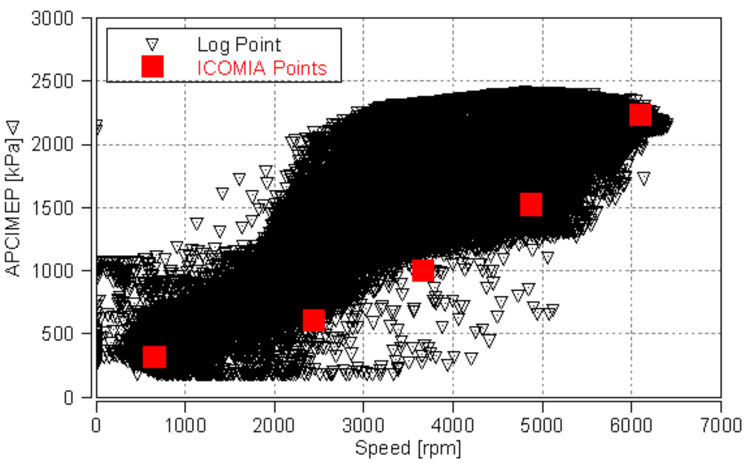

Figure 19: Endurance Boat and ICOMIA Speed/Load Points

During testing, some significant issues were discovered. High levels of oil dilution with fuel were again observed on the catalyst engine when compared to the production baseline. The increase in dilution over the baseline was slightly larger than what was observed on the dyno. Figure 20 summarizes the oil dilution test results. Although the increase in oil dilution is not directly related to the catalyst, it is a product of the cooling system design changes that were necessary to add the catalyst exhaust system to the engine. Further refinement of the engine cooling system is necessary to bring the dilution levels back in line with the current values.

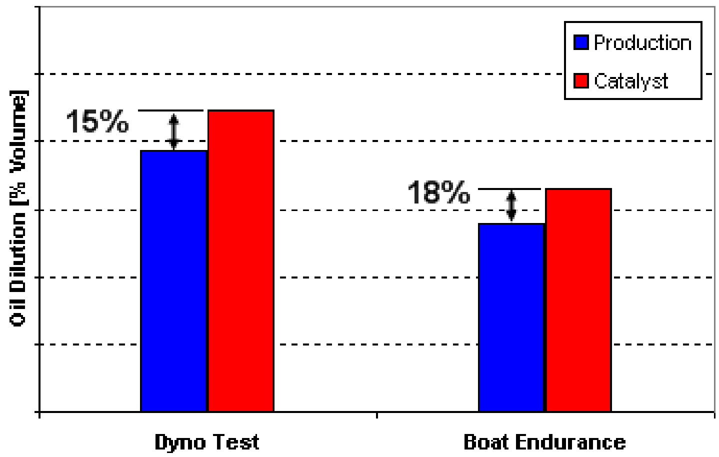

Figure 20: Oil Dilution Increase on Catalyst Engines

After the endurance test was complete, the engine was returned to Fond du Lac and dyno tested. The results were compared back to the baseline data and showed that the engine emissions and wide-open throttle performance had not degraded significantly over the course of the endurance test. Table 8 summarizes the emissions results before and after endurance for both the ITC and boat tests.

	ITC WOT			Boat ICOMIA		
Emissions	**0 hour**	**100 hour**	**Increase**	**0 hour**	**100 hour**	**Increase**
HC+NOx	2.32	2.99	0.67 (29%)	2.26	2.93	0.67 (30%)
CO (Mds 1-5)	87.2	109.1	21.9 (25%)	88.3	110.2	21.9 (25%)
CO (Mds 2-5)	4.7	12.8	8.1 (172%)	6.74	13.9	7.2 (106%)

Table 8: Pre and Post Endurance Weighted Specific Emissions [g/kW*hr]

The post-test inspection showed that the same catalyst mounting failure that occurred on the WOT engine also occurred on the boat endurance engine. Examination of the failed catalyst assembly demonstrated essentially the same signs of a lack of clamping pressure on the substrate.

An additional issue that was seen during boat endurance was failure of the post-catalyst oxygen sensor. A diagnostic check discovered that the output of the sensor was stuck at a fixed value indicating that the sensor likely came in direct contact with liquid water. When additional tests were run to better diagnose the issue, the sensor resumed its normal operation. The failure occurred 73 hours into the test. The sensor was left in the engine, and successfully completed the balance of the 100 hour test without incident. It remains unclear if the water that contacted the sensor was sea water which came up the exhaust pipe, or water that condensed on the inner surface of the pipe during extended operation at low speed or idle.

It is important to note that the primary purpose of the post-catalyst oxygen sensor is for catalyst monitoring. While the post-catalyst oxygen sensor was malfunctioning, the engine was still able to maintain adequate closed loop fuel control using the pre-catalyst oxygen sensor. The engine control software used to run the prototype engines in this project was based on production software used on Mercury Marine's catalyzed sterndrive and inboard engines. This software includes all of the on-board diagnostics (OBD) features required by CARB for marine engines

(OBD-M). While an evaluation of OBD-M on outboards was outside the scope of this project, some of the OBD-M features in the software were enabled prior to testing. The diagnostic check referred to earlier was one of these features.

At the conclusion of engine testing, 200 hours of durability testing had been compiled, along with approximately 175 hours of development testing. This level of testing reflects only a very small fraction of the time required to validate a production outboard engine. A production program to introduce a catalyzed outboard with a design similar to that tested here would require over 12,000 hours of durability testing and an additional 6,000 hours of calibration and development testing.

4 STATUS OF THE TECHNOLOGY

This project has resulted in the creation of the first catalyst equipped four-stroke outboard engine. Testing has shown that an outboard equipped with closed loop fuel control and a catalytic converter is technologically feasible, and will reduce HC+NOx emissions to a level that meets the CARB four-star super ultra low emissions standard. Equivalent CO emissions compliance was achieved on the prototype engines with the alternate 25 g/kW*hr standard for modes 2 through 5 currently available to sterndrive and inboard engines over 6.0L in displacement.

This project also exposed a number of significant technical challenges that must be overcome before this technology can be successfully brought to market. In that regard, this project provided a valuable foundation that future production catalyzed outboard programs can be built upon. While this project showed that closed loop fuel control in combination with catalytic converters is a technology that is not yet ready for production on outboard engines, none of the issues demonstrated here suggest that eventual implementation of this technology is impossible. Table 9 provides a general summary of the issues encountered here and how they would be addressed. A longer durability test program, which would include running engines to their full useful life, would be required to determine if any other issues would need to be addressed before bringing this technology to a production engine program.

Category	Issue	Plan for Resolution
Cooling System	Excessive oil dilution	Additional development testing and design iterations focusing on rebalancing the cooling system
	Condensation in exhaust and lube systems	
	Transient response	
	Catalyst temperature at idle	
Emissions	CO emissions at mode 1	Emissions are constrained by durability limits – may have little room for improvement
	Emissions aging unknown	Run full useful life test and evaluate results
Performance	Loss of WOT power & torque	CFD simulation and design iteration to improve exhaust flow losses
Exhaust System	Catalyst mounting failure	Revise mounting design to increase clamp load on the substrate
	Post-cat O_2 sensor failure	Determine the source of water
Engine Design	Increase in engine weight	Additional design refinement
	Increased package size	Investigate new solutions not considered in this study

Table 9: Summary of Open Issues

Future testing at Mercury Marine of the prototype catalyzed outboard engines will focus on addressing the above issues. Additionally, Mercury Marine will continue to examine its product line to understand how the eventual implantation of catalyst level emissions regulations will affect each engine family.

Based on the magnitude of the changes required to catalyze an outboard marine engine, a major redesign, development, and validation program will be required for each engine family. It is reasonable to expect that two to three years will be required per engine family to complete a catalyst conversion program. The investment required to create new or modified tooling for each engine family would be equivalent to approximately 30% of the tooling investment for a completely new engine. It has been estimated that the research and development (R&D) expense to convert an existing engine family over to catalyst technology could be in the range of 50% of the expenses associated with a completely new outboard engine, depending on the specific design of the base engine.

Mercury Marine currently produces six families of four-stroke EFI engines. For reference, the other major outboard manufacturers selling product in the United States each have between five and eight four-stroke EFI engine families. While each OEM could probably carry out some concurrent work on multiple engine families, catalyzing five to eight engine families would take a significant amount of time to complete, and require very large investments of capital and R&D expense. Assuming Mercury Marine has the resources and financial capacity to start one major outboard program per year, it could take up to eight or nine years from the start of the first program to convert the full fleet of Mercury's four-stroke EFI engines over to catalyst technology.

In the near term, Mercury Marine will continue to develop the prototype engines produced as part of this study, focusing on resolving the issues noted earlier. Once the major issues have been resolved, additional durability testing will be run to prove the capability of the design to perform as necessary throughout the required useful life. The results of this project and the continuing work at Mercury Marine will be used to provide guidance to future production catalyzed outboard projects.