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

ICAT Grant #06-01

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CARB Technical Seminar
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BRUNSWICK
GENUINE INGENUITY

Contents

Background & ICAT Project Overview

Background on Mercury Marine

- World's leading manufacturer of recreational marine propulsion engines
- $1.4 billion division of Brunswick Corporation (NYSE:BC) – down from >$2 billion
- Mercury provides engines, boats, services and parts for recreational, commercial and government marine applications
- Last American outboard engine manufacturer

Mercury Marine Outboard Products

- Engines range in power from 2.5 to 350 hp
- Used in freshwater and saltwater
- >40% market share
- Primary competitors are:
  - Yamaha
  - Suzuki
  - Honda
  - Bombardier

ICAT Project Objectives

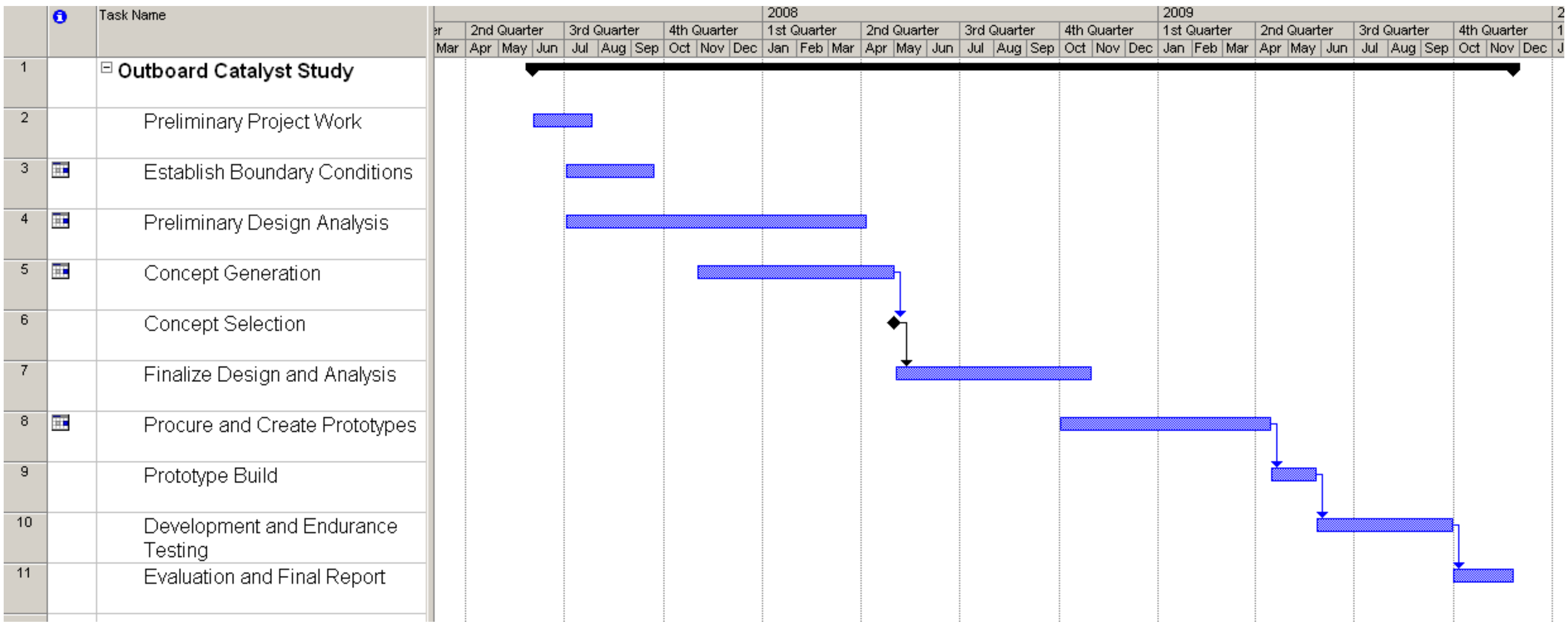
- To study and find solutions to the technical challenges facing catalyst implementation on outboards
- Build and test prototype catalyzed outboard engines
- Provide technical data to CARB that can be used to develop the targets and timeline for implementing more stringent outboard emissions regulations

ICAT Project Scope

- Examine four-stroke engines that already have EFI – typically this means engines above 25-30 hp
- Select two engine families and design a catalyst exhaust system, including capability for closed-loop fuel control
- Build running prototypes based on one of the above designs
- Conduct testing to measure emissions and performance; and get an initial indication of mechanical durability
- Conduct cost and implementation analysis

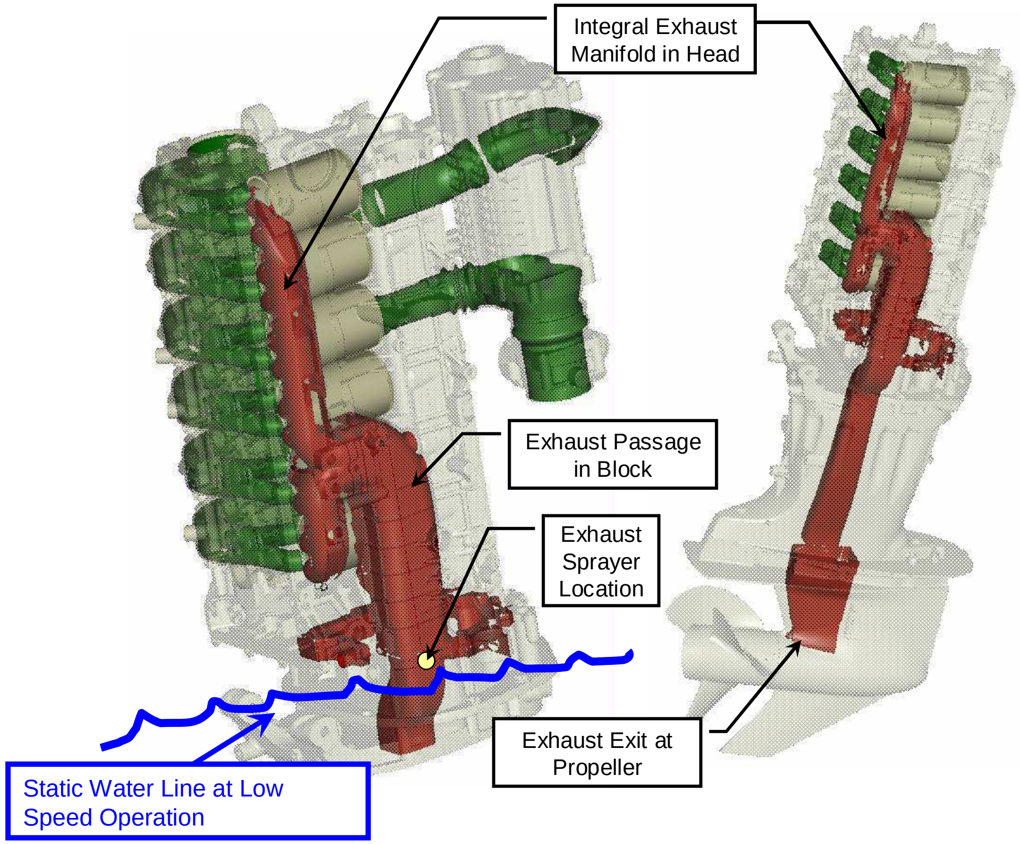
ICAT Project Schedule & Resources

- Overall project duration was approximately 2 ½ years
- Mercury Marine total HR > 18,700 hours
- Mercury Marine total project expense = $642,750
- CARB ICAT cost share = $475,000

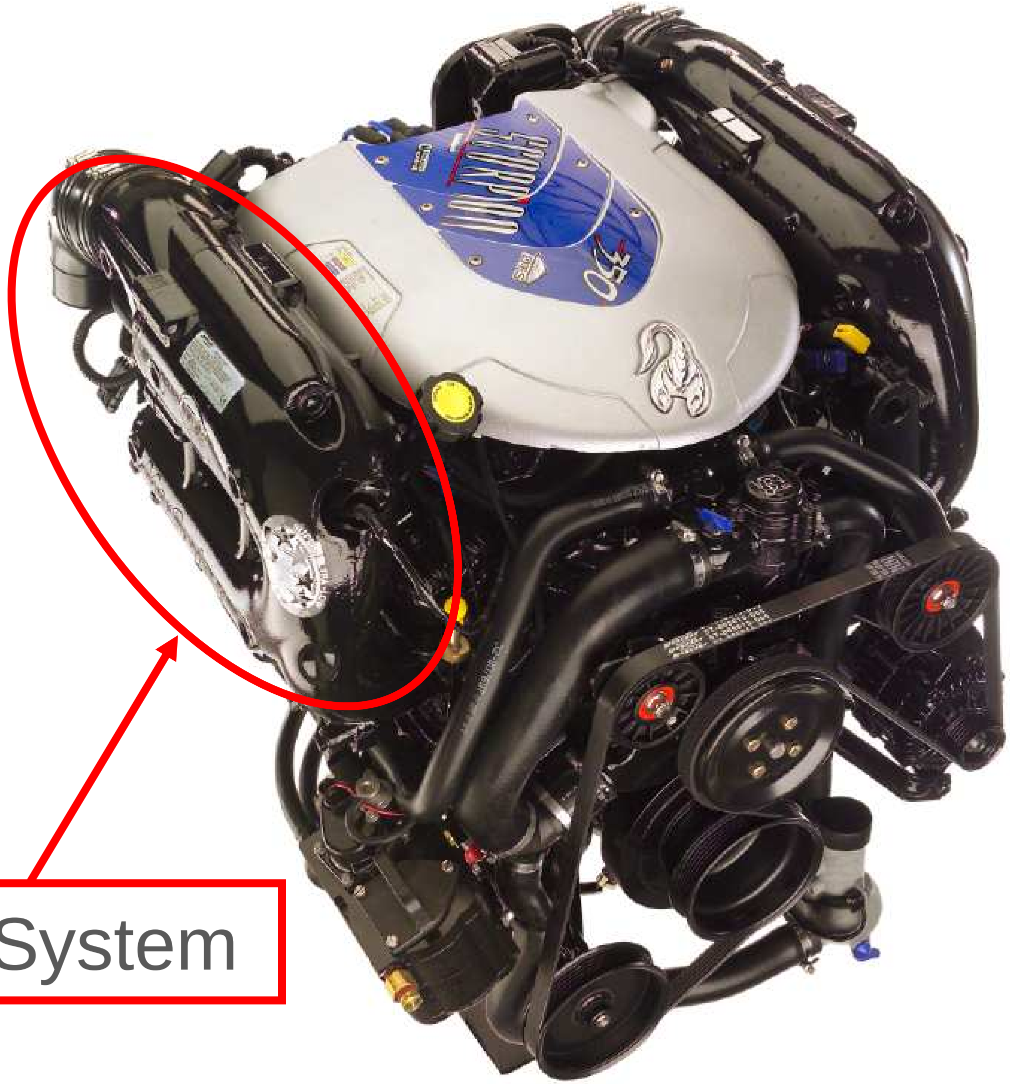


Outboard Engines – Current Design & Technology

Outboard Engine Layout



Sterndrive Engine Layout



Bolt on Exhaust System

SD/IB vs Outboard

Sterndrive/Inboard		Outboard
•Marinized automotive engines •Bolt on exhaust systems •Engine is mounted under the boat deck and is protected from water ingestion •Engine power to weight ratio is less critical to boat performance	⟷	•Purpose built marine engines •Exhaust system is integrated in major engine castings •Engine hangs off the back of the boat and is continuously exposed to water •Engine power to weight ratio is absolutely critical to boat performance

Catalyzed Marine Engines

- Testing at Southwest Research on SD/IB prototypes uncovered many issues especially during saltwater testing
- Mercury developed catalyzed SD/IB engines to meet 5 g/kW-hr HC+NOx standards for 2008
- Only some SD/IB technology will transfer to outboard
- Outboard marine applications are expected to be more challenging, especially with respect to:
  - Packaging
  - Water Intrusion
  - Heat Management

SD/IB vs Outboard Installations

Sterndrive

Outboard

Engine is protected from water inside the hull

Engine is fully exposed to sea water

Only the drive is exposed to water

Marine Engine Exhaust Emissions Standards

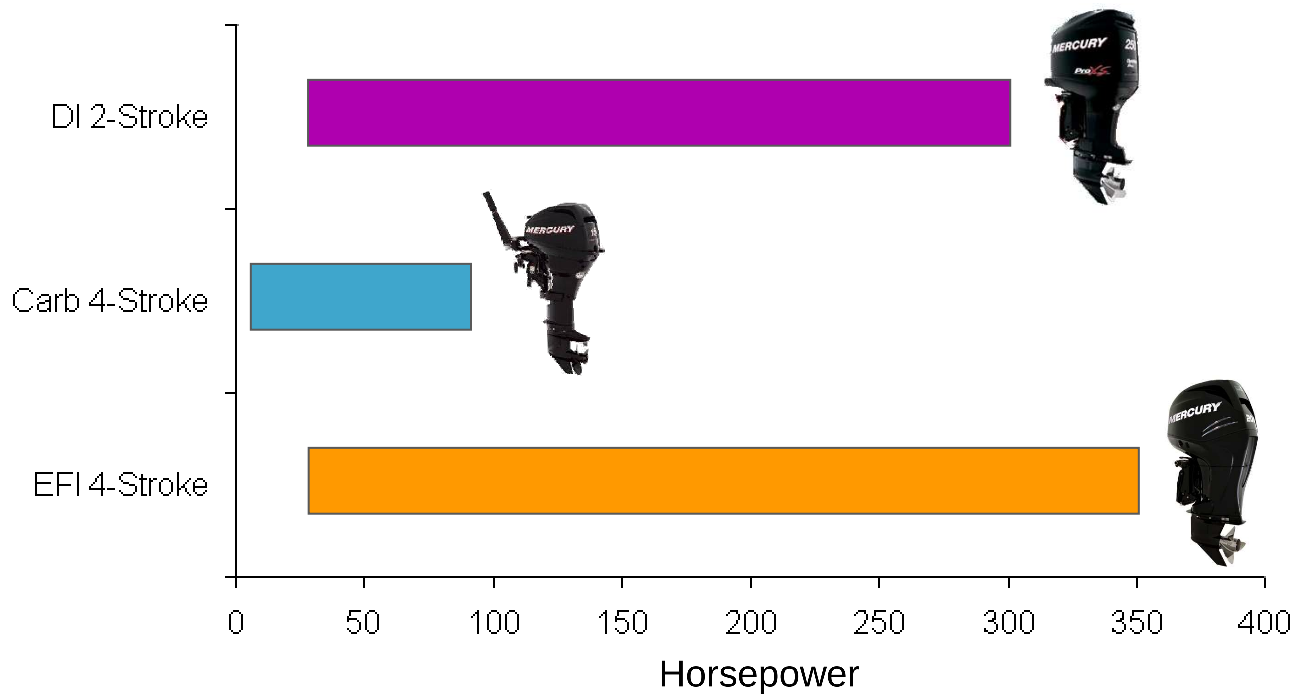
- Marine engine exhaust emissions are measured on the ICOMIA 5-mode test cycle
- Outboard engines available on the market today are a mix of 2-star and 3-star certified products

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 / 14 (2007)	NR
2008 (CO in 2010)-	4-star	5	75 / 25[3]

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

Outboard Engine Technology

- Outboard engines employ a range of different technologies – the three main types are:
  1. Direct-injection two-stroke
  2. Carbureted four-stroke
  3. EFI four-stroke



Target Engines – 60hp EFI Four-Stroke

- 1.0L inline four cylinder
- Vertical crankshaft
- SOHC, 2 valves/cylinder
- Sequential multi-port EFI
- Die cast aluminum block
- Semi-permanent mold aluminum head
- 3-star emissions

Target Engines – 200hp S/C EFI Four-Stroke

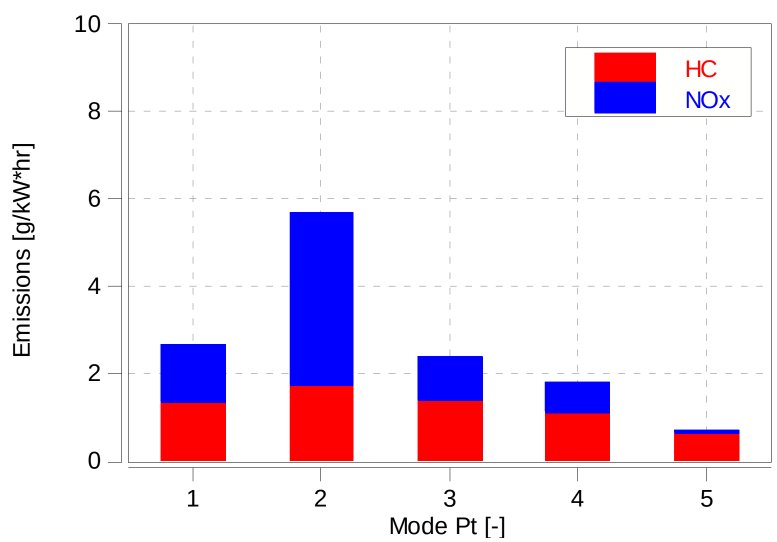
- 1.7L inline four cylinder
- Vertical crankshaft
- DOHC, 4 valves/cylinder
- Sequential multi-port EFI
- Supercharged w/ electronic boost control
- Electronic throttle and shift
- Lost-foam cast aluminum block and head
- 2-star emissions

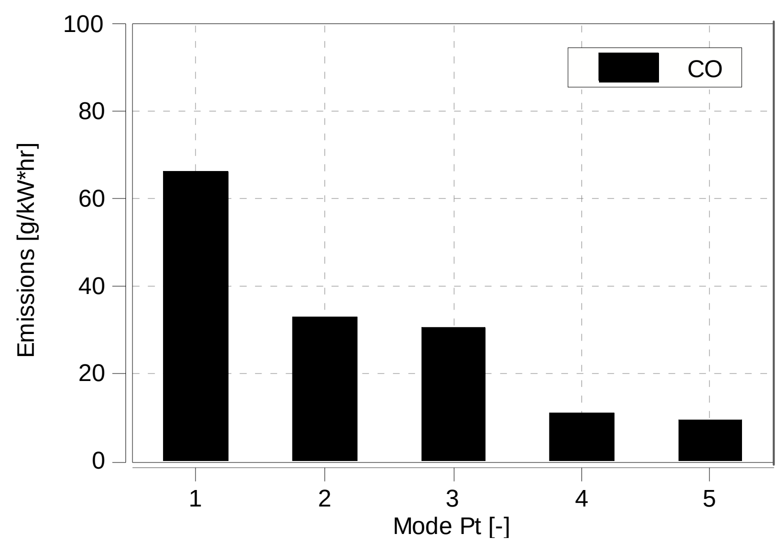
Boundary Conditions

Design Boundary Conditions – Catalyst Inputs

- 60hp and 200hp engines were dyno tested to measure power, exhaust gas temperature, flow, and emissions
- These inputs were used to determine:
  - Catalyst size
  - Cell density
  - Washcoat formulation
  - Thermal Load

Baseline Emissions – 60hp EFI





- HC = 6.44 g/kW*hr
- NOx = 6.82 g/kW*hr
- HC+NOx =13.26 g/kW*hr → 3-star
- CO = 151.3 g/kW*hr

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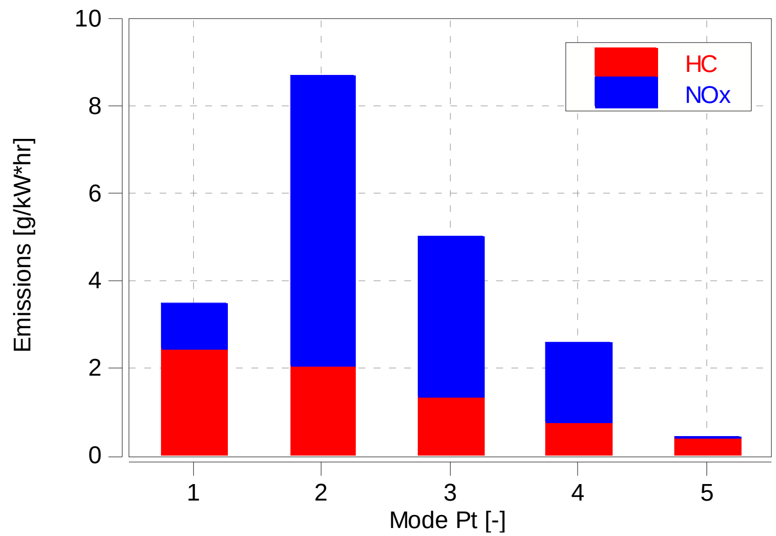
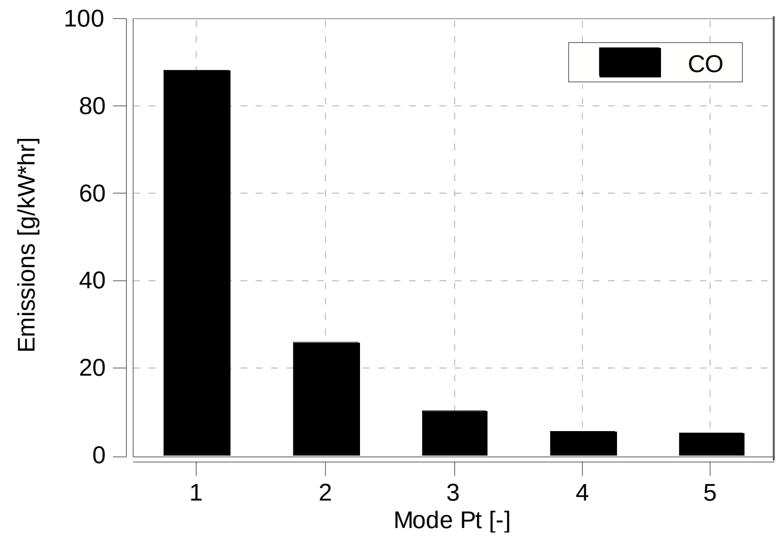
Baseline Emissions – 200hp S/C EFI Verado

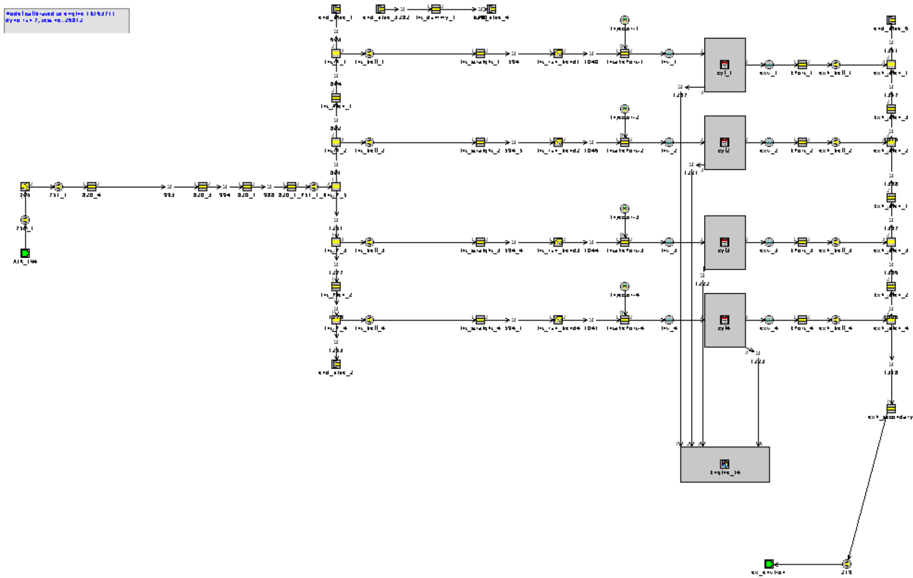


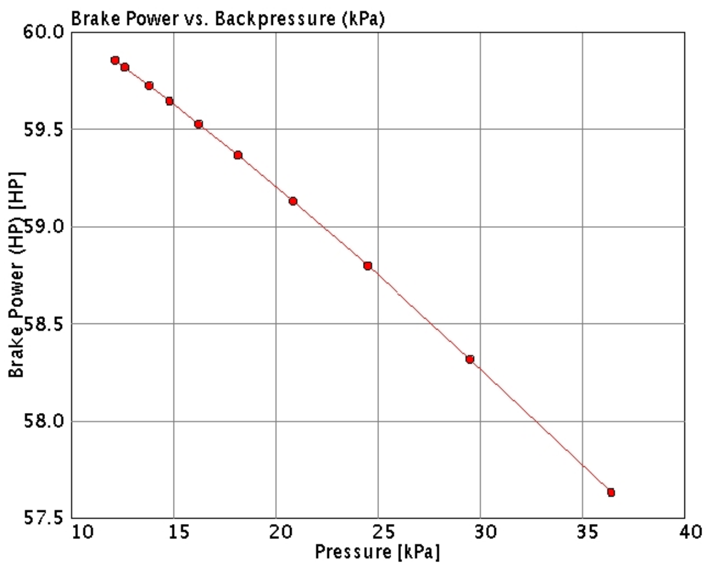


- HC = 7.21 g/kW*hr
- NOx = 13.02 g/kW*hr
- HC+NOx = 20.23 g/kW*hr $\rightarrow$ 2-star
- CO = 135.5 g/kW*hr

Engine Performance Simulation

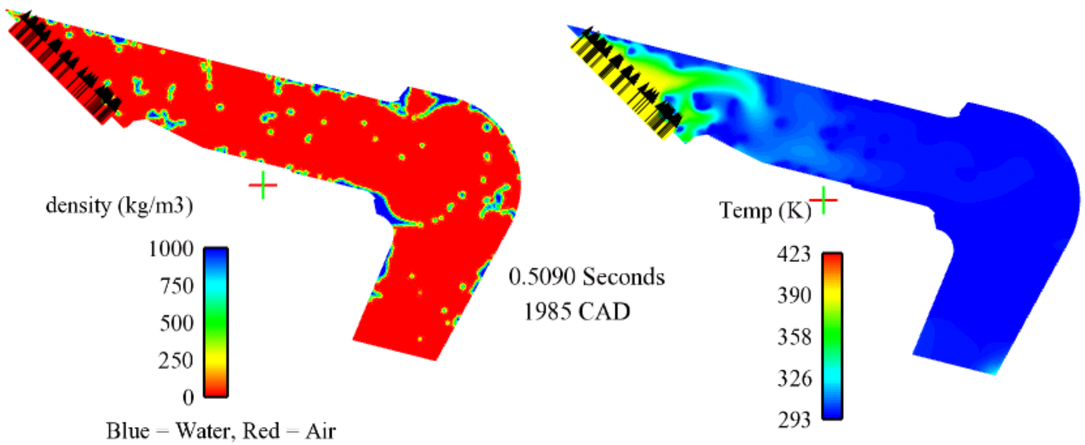
- Dyno testing and computer simulation were used to determine the additional exhaust back pressure, and performance impact of changing the exhaust system and adding a catalyst

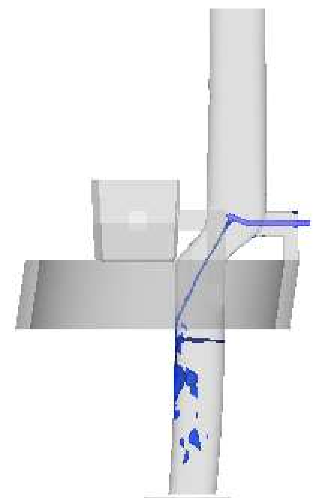




Water Intrusion Testing

- 60hp and 200hp engines were instrumented to measure pressure & detect water in the exhaust system
- A high-speed camera was installed in the 200hp engine exhaust system
- Based on test data, multi-phase 2D & 3D simulations of the exhaust system including exhaust flow and water were created





Water Intrusion Testing

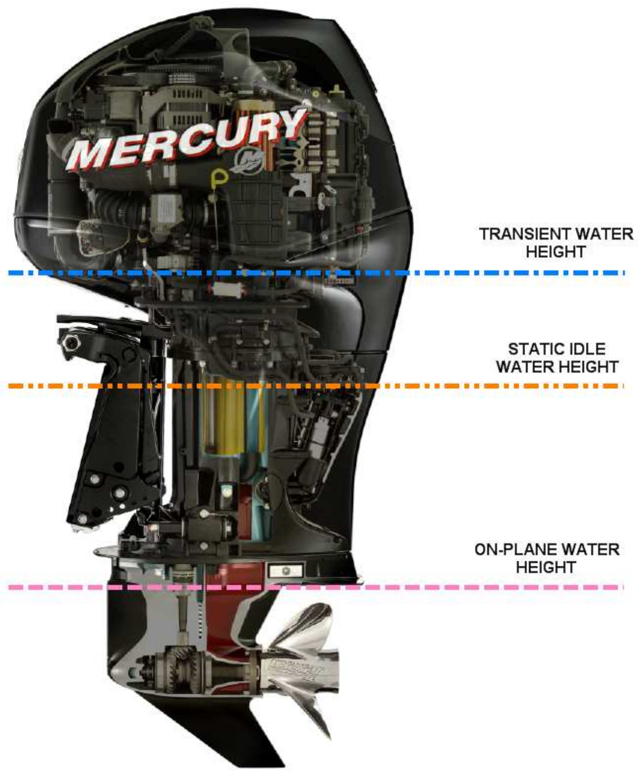
- The engines were then rigged on test boats with a high speed data acquisition system.
- Over 100 different tests were run examining the effects of boat type, engine position, exhaust system configuration, and operating condition.





Water Intrusion Testing

- Baseline testing showed that water routinely entered the powerhead through the exhaust system
- Design modifications were tested that significantly reduced the height of water in the exhaust system – critical for catalyst and oxygen sensor durability



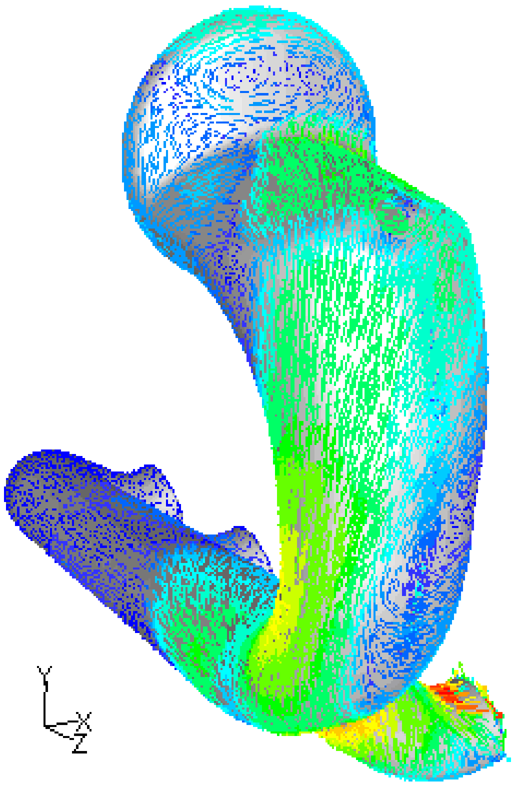
Catalyst Engine Design

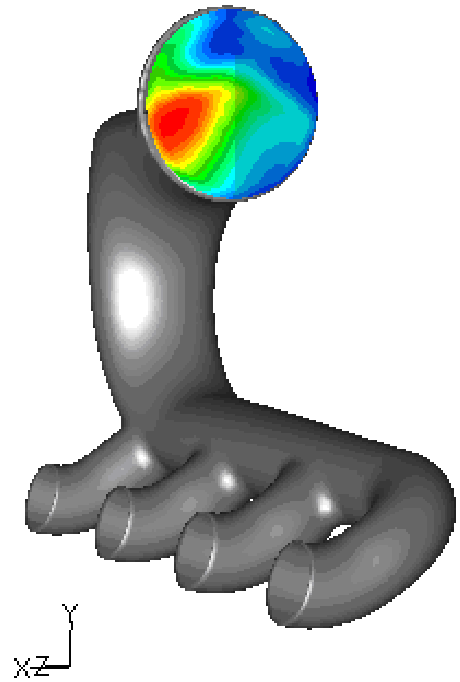
Catalyst Engine Design

- Multiple design concepts were generated for each engine
- A selection matrix was used to rank each concept against the program acceptance criteria and choose a primary path
- Acceptance criteria included:
  - Potential for emissions reduction
  - Minimize loss in performance
  - Manufacturability
  - Durability
  - Serviceability
  - Cost

Exhaust System

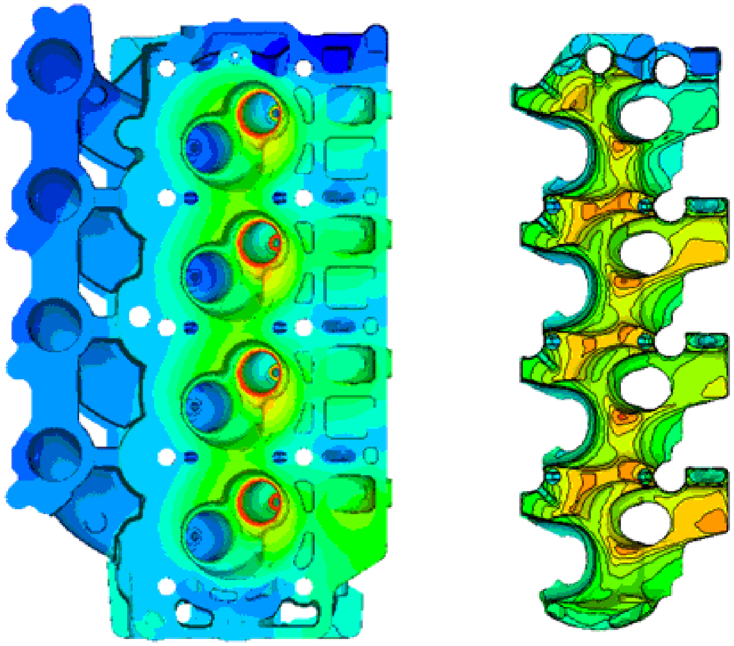
- 3D simulation was used to optimize the flow through the catalyst and determine the best positions for the oxygen sensors





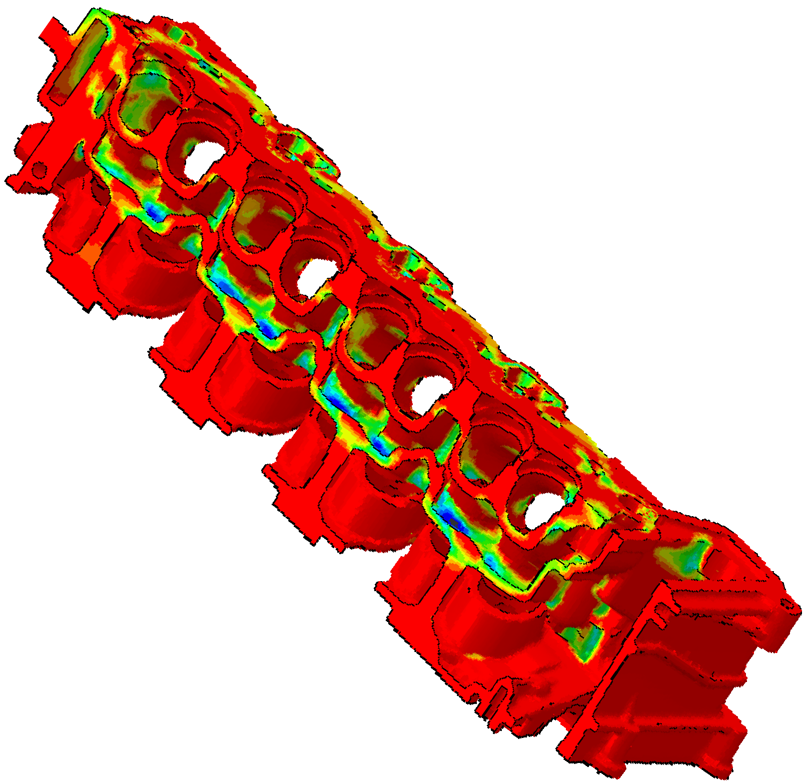
Cooling System

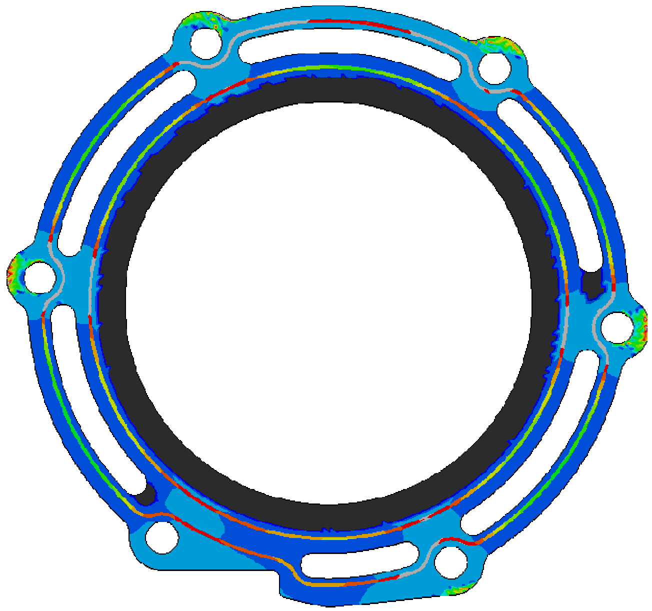
- 3D CFD analysis was used on the new and revised water passages to optimize coolant flow through each of the components
- Thermal inputs were added to the models to determine coolant temperature, total system heat input, and surface temperature
- Because the catalyst exhaust system rejects more heat to the cooling system, the analysis showed the potential for issues



Structural Analysis

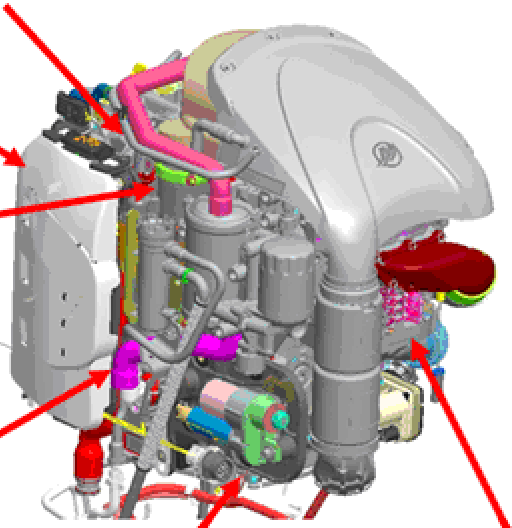
- Structural analysis of the catalyst designs were carried out to verify acceptable stress levels under thermal and mechanical loads and to ensure adequate clamping load across bolted joints





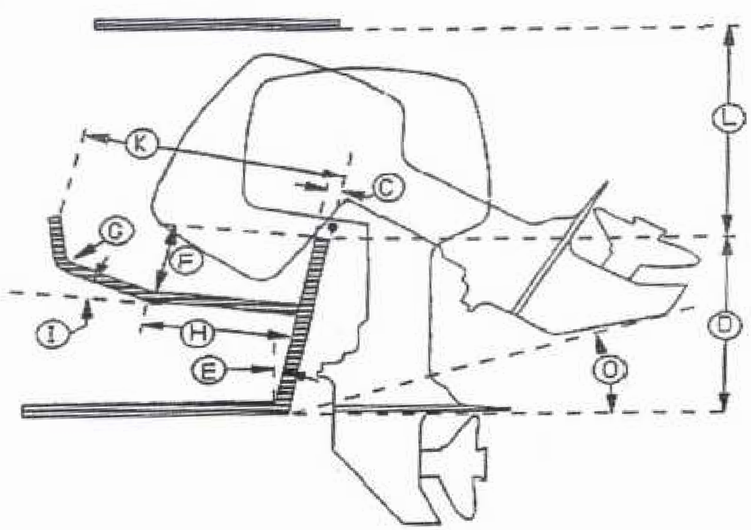
Detailed Packaging Analysis

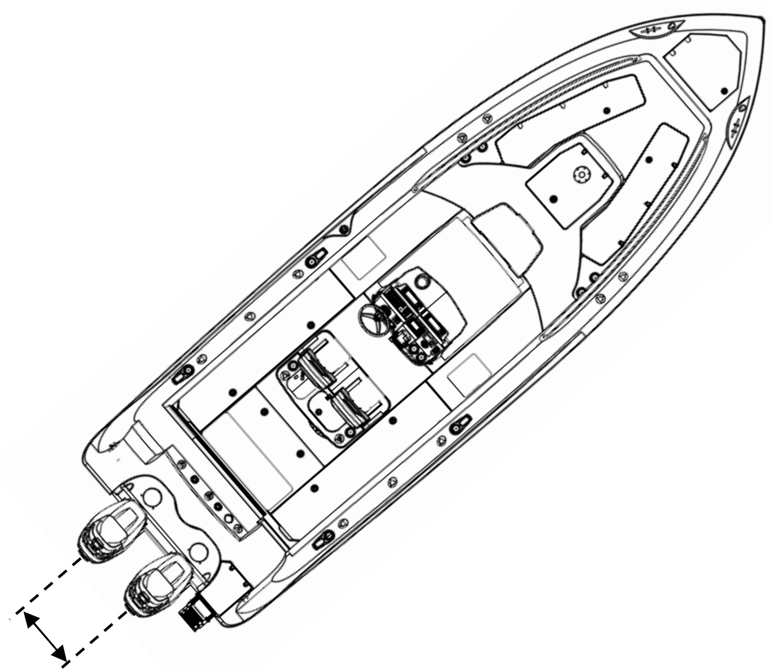
- CAD assemblies of the catalyst outboard engines including all of the peripheral components were evaluated to determine which components need to move to accommodate the new exhaust system, and whether there was enough room for the repackaged engine under the current cowling



Package Size

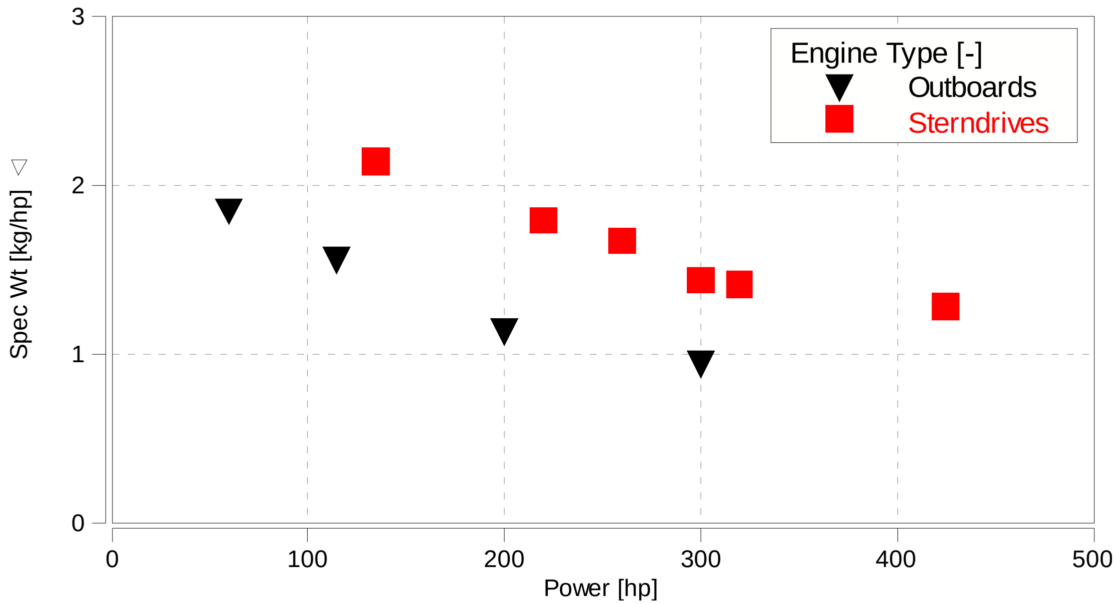
- Outboard engine size must be kept to a minimum – the addition of a catalyst exhaust system has the potential to increase the size of the top cowl
- American Boat & Yacht Council (ABYC) standards govern major external dimensions – exceeding these can cause issues with engine-to-boat or engine-to-engine clearances
- The 200 hp Verado was packaged within the current envelope – the 60 hp EFI would require a larger top cowl





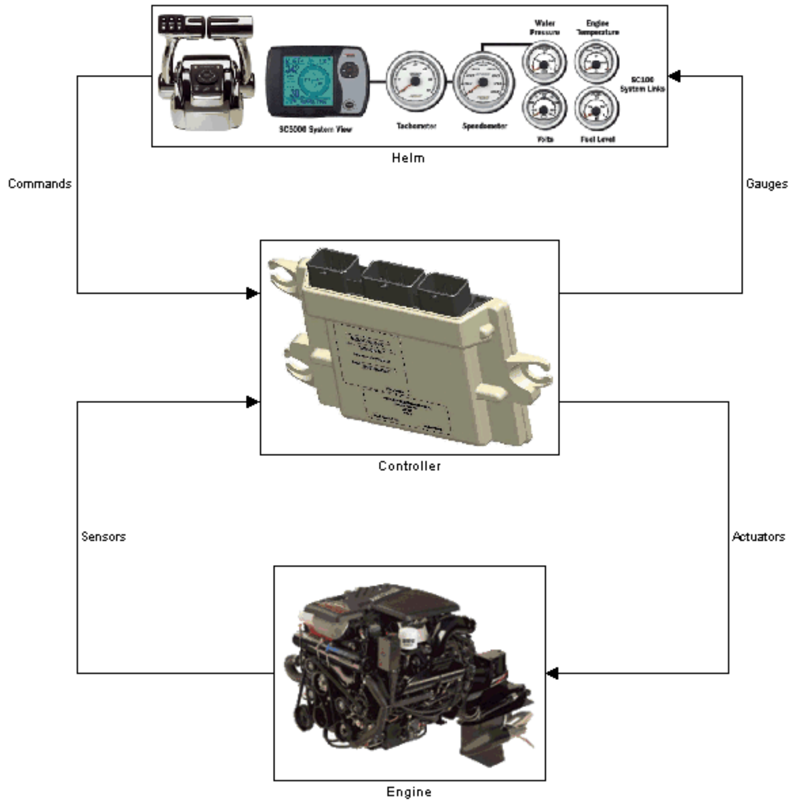
Engine Weight

- For a given power level, outboard engines have significantly lower weight than sterndrives
- The addition of a catalyst exhaust system increased the weight of the two engines under investigation by 3-4%



Engine Control Software

- The engine control software and ECU developed for the catalyzed sterndrive engine was adapted for outboard use
- This software and ECU had never been tested on an outboard, and required the addition of boost control for the 200hp engine



Prototype Build & Test Results

Prototype Catalyst Outboard Selection

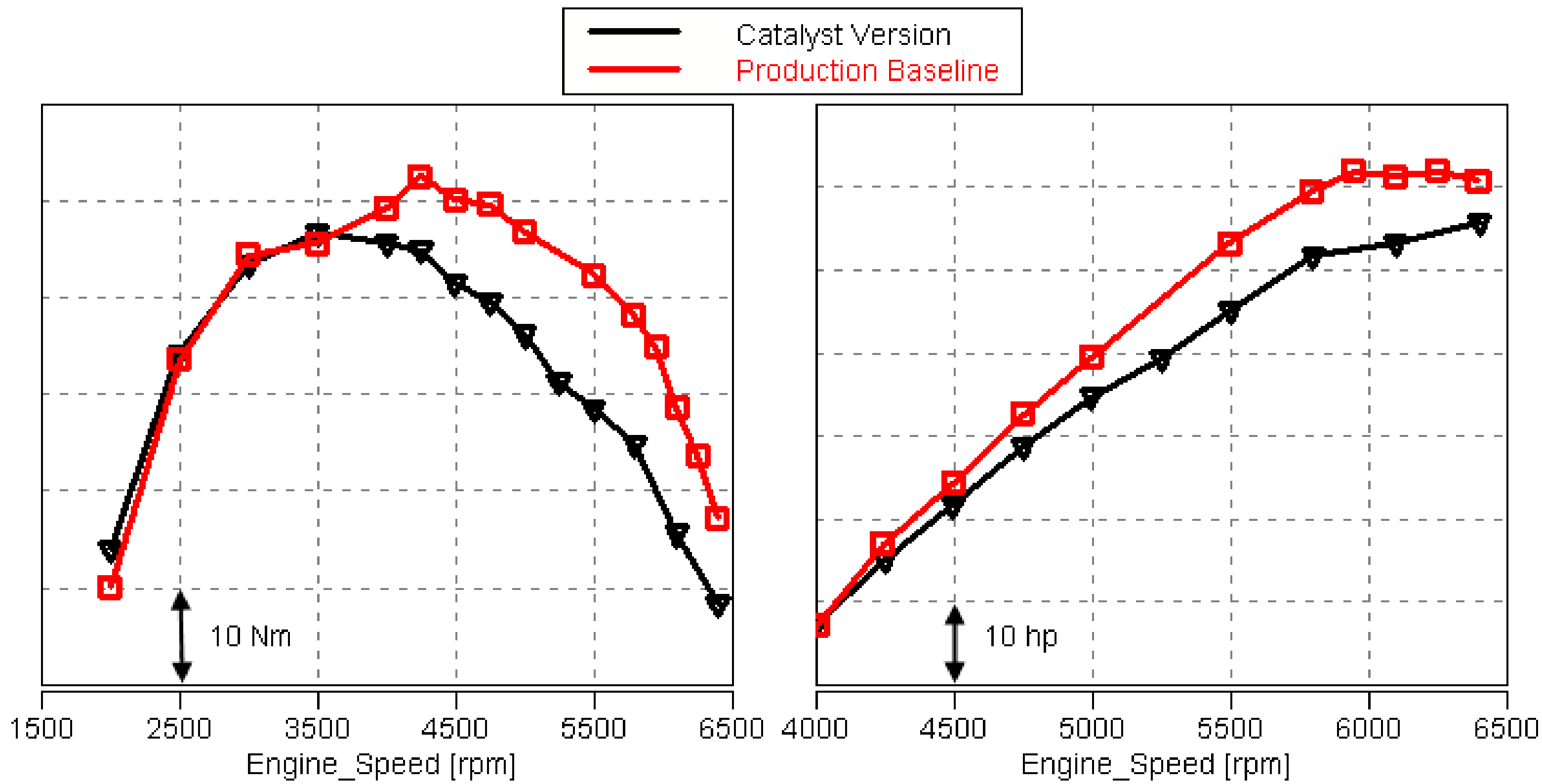
- The 200 hp S/C EFI Verado was chosen for prototyping
- The benefits of choosing this engine were:
  - Scalable design attributes to higher and lower powered engines
  - Higher baseline emissions
  - Harsher exhaust environment – i.e. higher flows and temperatures

Prototype Engine Build

- Building the catalyst engines required a number of prototype parts, including cylinder blocks, cylinder heads, exhaust manifolds, catalyst housings, and catalyst assemblies
- In addition to these, other new parts needed to be designed and fabricated including gaskets, fasteners, brackets, the wiring harness, and starter motor
- The head and block castings were made at Mercury's production lost-foam casting facility using prototype foam molding and assembly tools, and were machined and assembled on Mercury's production lines
- Other prototype parts were created in Mercury's Model Shop, or supplied by outside companies
- In total, four engines were built for development and durability testing

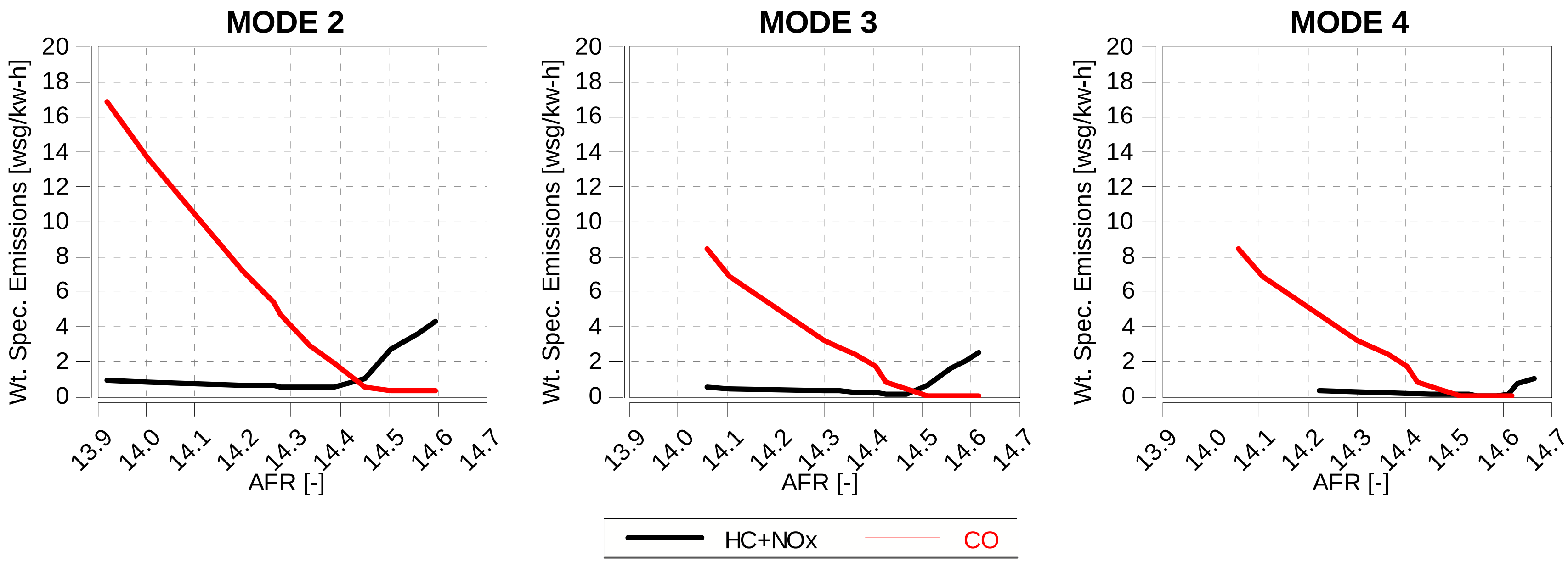
WOT Performance

- Wide open throttle (WOT) testing showed a reduction in performance
- Performance loss was mostly due to increased back pressure in the exhaust system



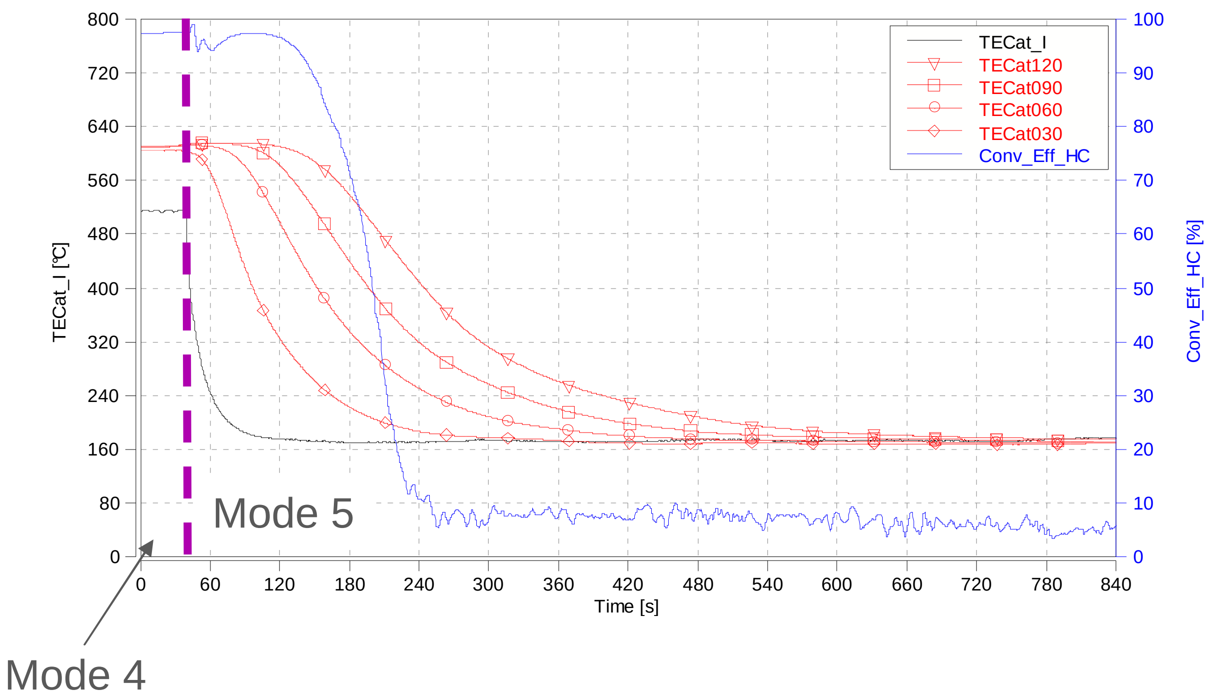
Emissions at Part Load (Modes 2-4)

- The calibration at modes 2-4 was optimized to minimize HC+NOx and CO
- Calibration parameters included target air/fuel ratio and fuel perturbation parameters



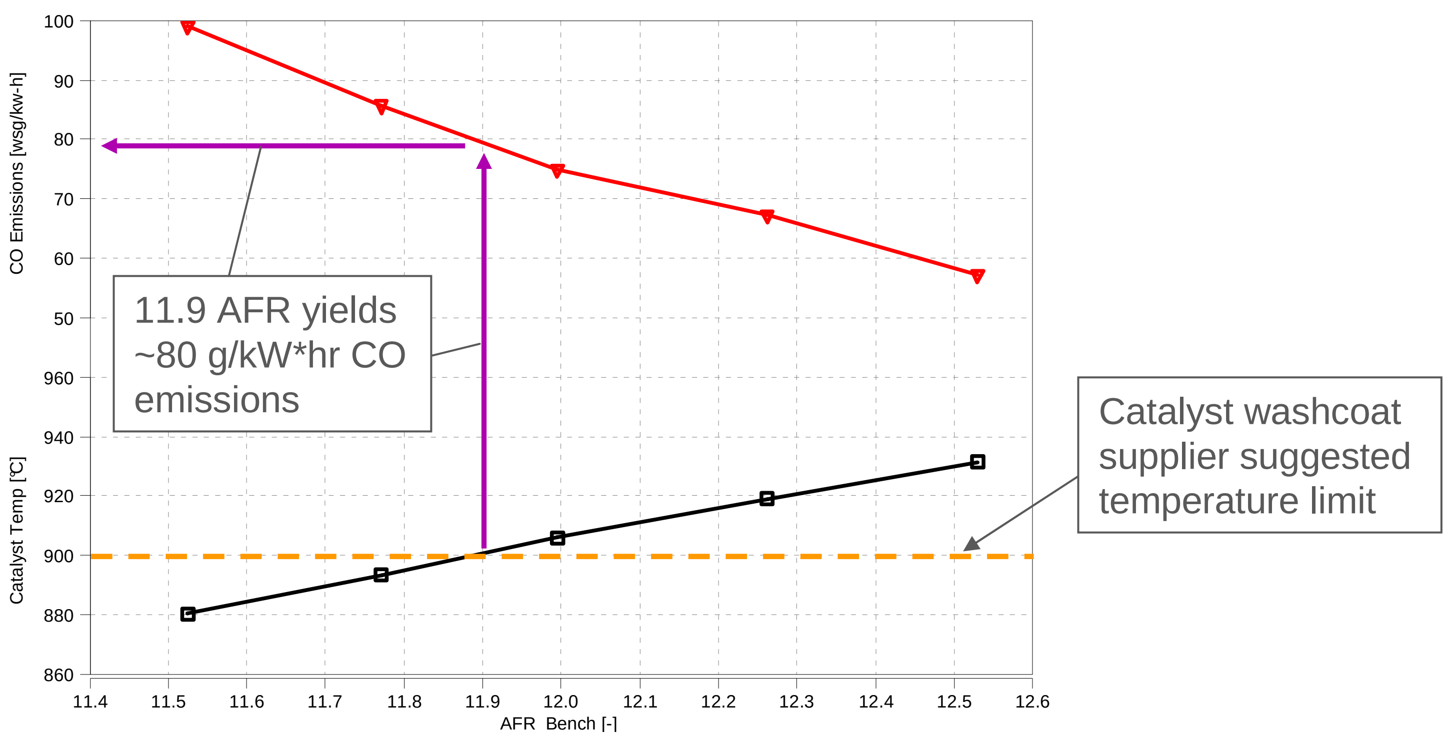
Emissions at Idle (Mode 5)

- Because of the large water jacketed surface area of the exhaust manifold, the catalyst inlet exhaust gas temperature at mode 5 was too low to sustain significant catalytic conversion
- Idle HC emissions with a hot catalyst were 0.03 g/kW*hr and 0.35 g/kW*hr after the catalyst had "gone out"

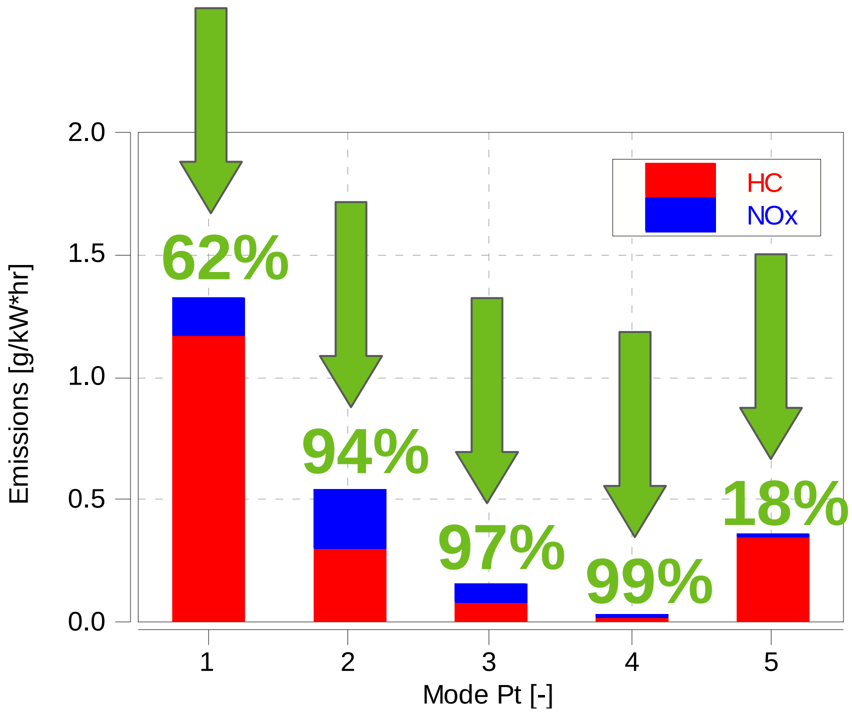


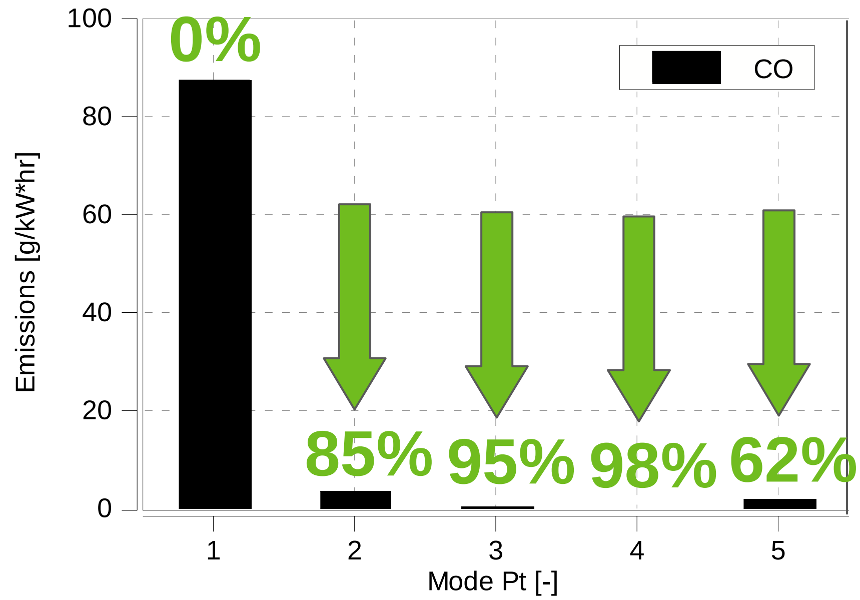
Emissions at Rated Power (Mode 1)

- Air/fuel ratio calibration at mode 1 is limited by catalyst temperature
- A leaner Mode 1 calibration would yield lower CO emissions but have unacceptably high catalyst mid-bed temperatures



Overall ICOMIA Emissions





- HC+NOx = 2.41 g/kW*hr → **88%** reduction from baseline
- CO = 93.9 g/kW*hr → **31%** reduction from baseline
- 6.4 g/kW*hr CO modes 2-5 → **86%** reduction from baseline

Emissions Aging

- Catalyst aging was outside the scope of this project and was not determined
- Aging factors can be estimated using data from Mercury's catalyzed sterndrive and inboard engines

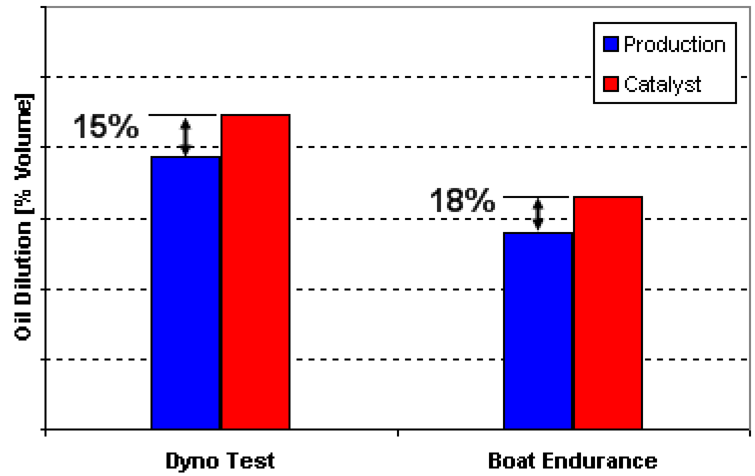
	Wt. Spec. Emissions [g/kW*hr]		Aged Margin to 4-Star Limit [%]
	Green	**Aged**	
HC+NOx	2.41	4.2	16
CO (5 Mode)	93.9	112	-49
CO (Modes 2-5)	6.4	18	28

Cooling System

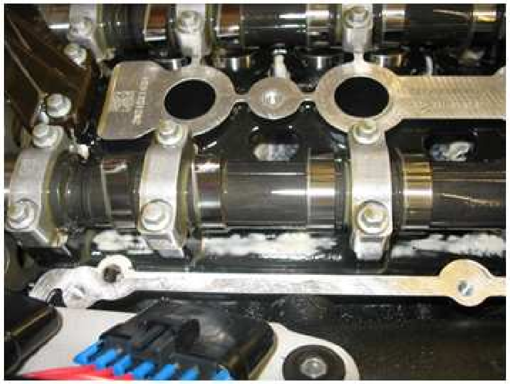
- The initial cooling system configuration experienced thermostat cycling issues causing excessive coolant temperatures at some operating points
- This was partially corrected by lowering the thermostat temperature
- Lowering the thermostat temperature has some negative consequences:
  - Lower oil temperature increasing the level of oil dilution with fuel
  - Lower cylinder head and oil sump temperature increasing the amount of water condensation in the oil
  - Lower exhaust manifold wall temperatures increasing the amount of condensation in the exhaust
  - Higher water flow rate through the engine lowering the flow through the charge air cooler and oil cooler

Oil Dilution & Condensation

- Increased oil dilution was measured on the dyno and during boat testing

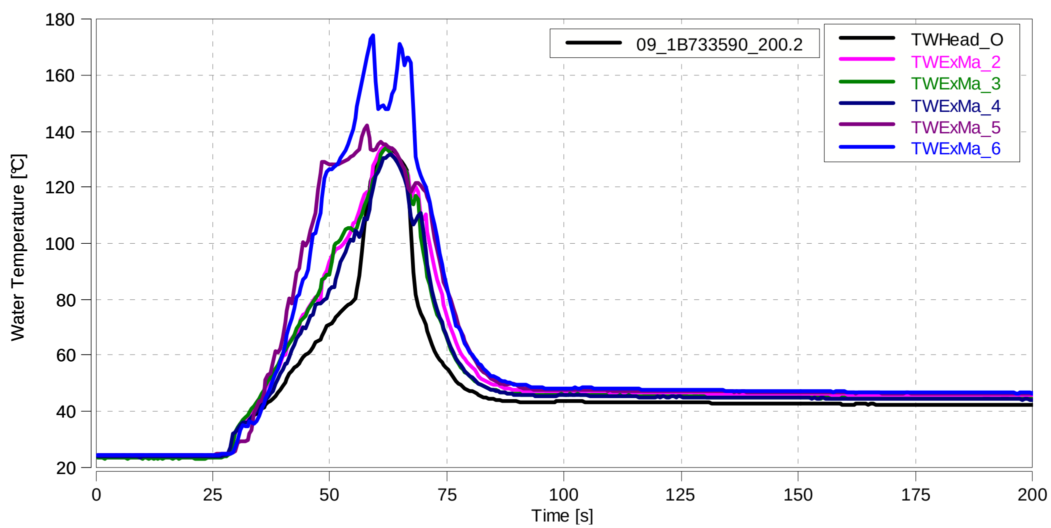


- Condensation in the exhaust and lube system was observed during testing



Transient Cooling System Testing

- Changes made to the cooling system to improve the steady-state performance decreased the ability of the system to handle rapid changes in thermal load and flow rate
- During one rapid acceleration test the cooling system was unable to purge a pocket of air in 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 melted a hole through the manifold inner wall



WOT Endurance Testing

- One of the prototype engines was tested for durability at continuous wide-open throttle operation
- The engine was broken-in on the dyno
- Power and emissions were also checked before it was rigged in Mercury's Indoor Test Center
- The engine ran for 100 hours at 6,100 rpm WOT

WOT Endurance Results

- No major failures occurred during testing
- After the test was complete, the engine was rigged on the dyno again for a post-endurance check
- Power and emissions were close to the pre-test values
- After testing, a visual inspection of the catalyst revealed that the substrate mounting had failed

Boat Endurance Testing

- A second prototype engine was tested for durability during “normal” customer operation
- The engine was broken-in on the dyno
- Power and emissions were checked before it was sent to Mercury’s saltwater test site X-Site in Panama City, Florida and rigged on a 22’ Velocity
- The engine ran for 100 hours over a simulated ICOMIA cycle

Boat Endurance Results

- During testing, higher than normal oil dilution was noted
- At 73 hours of testing, the OBD-M system flagged a stuck post-catalyst O2 sensor – this fault typically occurs when an oxygen sensor gets wet
- During the investigation, the sensor began to function normally again and was left in the engine for the duration of testing
- After boat testing was complete, the engine was returned to Fond du Lac for post-endurance tests
- Dyno testing showed power and emissions were similar to the baseline levels
- After testing, a visual inspection of the catalyst revealed that the substrate mounting had failed in the same manner as the catalyst in the WOT engine
- During post-endurance testing, the post-cat O2 sensor functioned normally
- The source of water that caused the sensor to temporarily fail during endurance is unknown – the likely sources are sea water that travelled up the exhaust pipe or condensation from the exhaust manifold

Status of the Technology

Emissions

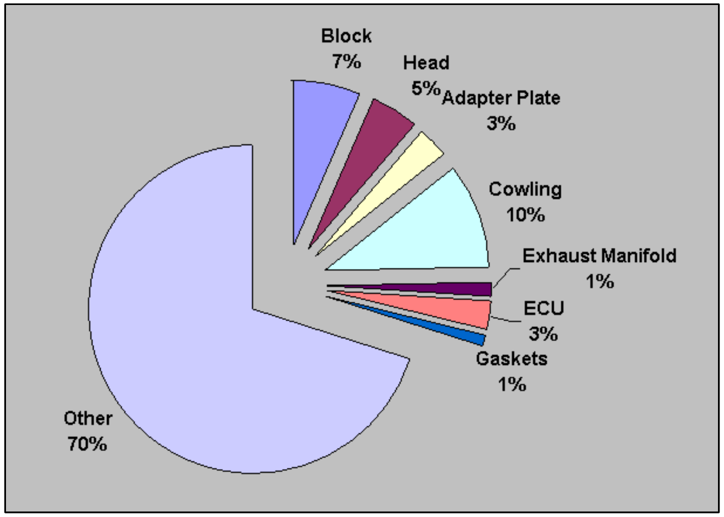
- Initial HC+NOx emissions on the prototype engines met the Sterndrive and Inboard 4-star standard of 5 g/kW*hr
- Aged emissions of a catalyzed outboard are unknown – initial estimates show they may still be under the 5 g/kW*hr standard
- CO emissions do not meet the 4-star standard of 75 g/kW*hr
- However, most of the CO emissions are generated at mode 1 – wide-open throttle, rated engine speed
- Excluding mode 1, CO emissions at modes 2-5 are within the 25 g/kW*hr alternate standard available for SD & IB engines > 6.0L

Durability

- Initial durability testing of the prototype catalyzed outboards yielded positive results – none of the issues encountered in this study are “show-stoppers”
- Further development work should yield solutions to these problems
- During the course of this project, 200 hours of durability test hours were compiled, along with 175 hours of development testing
- Mercury’s standards for a production catalyst outboard engine program would require approximately:
  - 12,000 hours of durability testing
  - 6,000 hours of calibration and development testing
- Significantly more test hours are required to fully understand all of the issues that catalyst outboards will face

Production Project Expense & Timing

- Each of the major components that were changed during this study would need to be retooled for production
- 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.
- A production catalyst outboard program would likely require 2-3 year to complete – Mercury has six EFI four-stroke engine families
- At a rate of one new program per year, Mercury could convert its entire EFI four-stoke line to catalyst technology in eight to nine years



Other Considerations

- Each of the major outboard engine manufacturers has between four and six small carbureted four-stroke engine families
- The results of this study do not clearly indicate the emissions reduction potential or durability issues that those engines may have

Questions?